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HANDBOOK ON AEROMAGNETIC SURVEYING

Metodicheskoye rukovodstvo po aeromagnitnoy s'yemke [Handbook on Aeromagnetic Surveying], 1955, Moscow, Pages 3-146

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INTRODUCTION

Soviet geophysicists were the first to create an apparatus with which to take magnetic measurements from aircraft and to work out a method for use in the field for geological prospecting. The first experimental flight with an aerial magnetometer was made on 19 July 1936 by A. A. Logachev and A. T. Mayboroda, between Novogorod and Valday (cf. Logachev 1936).

Millions of square kilometers of Soviet territory have now undergone magnetic survey from the air. This resulted in the discovery of new iron-bearing regions with large resources, while valuable data on the geological structure of extensive territories have been obtained. This data is being employed successfully in the compilation of geological charts and in selection of areas offering good prospects for the discovery of mineral resources.

Magnetic studies may readily be made from the air over territories inaccessible to study from the ground. This makes it possible to follow the major structural forms without interruption over all types of land and water surfaces.

The comparability of the findings of aerial magnetic surveys conducted on a large scale and with high accuracy and geological data for given regions makes it possible to examine changes in the magnetic field over a geological region as a whole and to identify special regional features of the magnetic field and the interrelation thereof with peculiarities of geological structure. Individual magnetic anomalies, which are usually studied from the ground, are now examined not in isolation from the general nature of the magnetic field but as a consequence of general changes reflecting geological structure.

This makes possible a fuller and better grounded analysis both of the general character of the magnetic field and of magnetic anomalies identified therein.

The completeness and the logic of the analysis of magnetic field improve particularly with accumulation of factual information on the geological structure of its individual parts, this information being taken as datum points for analysis of changes in the magnetic field over the entire territory under study.

Analysis of the magnetic fields of large territories with the assistance of geological data and geophysical data gained on the ground opens the way to the determination of regional geophysical signs indicating the possibility of finding given resources in specific areas in a manner analogous to that employed in learning the general geological situation.

Maps of terrestrial magnetism obtained by aerial survey constitute a new and significant step forward because they represent the taking of measurements of high accuracy, over a fine network of routes, within a brief period of time, encompassing very substantial territories. This is either impossible or exceedingly costly if done on the ground.

Magnetic surveys may be made from the air at various altitudes. The only limiting factors are topography and the ceiling of the aircraft. There is a significant relationship between altitude and the detail of the findings. As the survey altitude increases the magnetic effects of small geological forms are lost. A magnetic chart compiled from data obtained from a high altitude flight will reveal only major geological features. The intensity and shape of an anomalous magnetic field produced by rock of the crystalline foundation and found in areas with thick sedimentary overlaps of nonmagnetic rocks will be analogous in intensity and shape to an anomalous magnetic field observed by aerial survey over a territory with exposed crystalline rocks at an altitude equal to the thickness of the nonmagnetic superficial strata.

The present handbook is based on the experience accumulated in applying aerial magnetic surveying to resolve various geological problems. There is no need to argue the fact that the possibilities to which aerial magnetic surveys may be put in the prospecting of mineral resources have not been exhausted. The theory, techniques, and procedures are constantly undergoing improvement and new possibilities for more effective employment of this method of high speed geological study of the enormous territory of the Soviet Union are opening up.

Further improvement in the geological efficiency of aerial magnetic survey is a major challenge to geophysical prospectors. The geological results of an aerial magnetic survey, consisting in conclusions as to the geological structure of the region under study, the identification of areas offering good prospects and the pinpointing of sites for prospecting, as well as compilation of properly grounded recommendations as to the direction, initial scale, and types of further geophysical and geological prospecting of these sites could be a great deal more complete and accurate than is presently the case if the organization, techniques, and methods of aerial magnetic research were improved accordingly.

In the field of the techniques of aerial magnetic prospecting, the progress made in recent years is quite significant although many valid possibilities for the further improvement of surveying techniques have not been employed.

We know that in very rugged country the detail of the surveys is limited by the high altitudes at which flights have to be made over deep valleys. Over plain country the survey may be taken from a more or less constant, low altitude. However surveys on a scale more detailed than 1:50,000 cannot be justified economically. The main reason for this is that there is a given flying speed at which fairly small details in the field, necessary for large scale surveys, disappear or are recorded inaccurately due to the inertia of the instruments.

Two directions are open for increasing the scale of aerial magnetic survey. One is acceleration of the rate at which the magnetic field is recorded by automatic aerial magnetometers and the other is the use of helicopters for work where surveys on a large scale are desired. The latter is the more practical solution of the problem because high speed aircraft cannot be used for large scale mapping in high mountain areas with very broken topography even if equipment with a significant diminution in the so-called "time constant" were developed.

Much attention must be given to stricter adherence to readily recognized landmarks for locations entered in the topographical map, the accuracy with which altitude is determined over the entire length of each route, and the development of methods for objective recording of the routes traversed and the altitude of the aircraft above ground level over its entire course. Topographical maps of the necessary accuracy are absolute requirements for surveys of high accuracy.

Objective recording of the routes traversed is possible in one of 2 ways, (a) continuous or selective photography with recording of the time, or (b) use of geodesic radar. Experience has shown that photography is a good method for objectively checking back over the route traversed but is is incapable of improving the plotting of the route. The latter problem, which is most important, is best solved by radar.

The problem of recording the altitude of the aircraft above ground level over the entire route is resolved satisfactorily by simultaneous employment of the radio altimeter and the barometric altimeter, with automatic recording.

Accurate piloting of the aircraft over the given route and objective recording of the coordinates over the entire course worked are important conditions for the taking of aerial magnetic measurements of high precision.

Precision measurements are a necessary but inadequate condition for increasing the geological effectiveness of aerial magnetic surveying. Given accurate and precise measurements, the results of the method are affected dicisively by rational choice of routes (for height, proximity, and direction) and maximum employment of the data obtained as to the magnetic field in prospecting the territory, with allowance for all the geophysical and geological data for the district.

It is to be borne in mind that the concept of geological effectiveness includes questions of cost. Therefore the develop— ment of rational method of conducting aerial magnetic surveys, beginning with the planning and finishing with the compilation of a geological report, must pursue the object of resolving the geological problem as fully as possible with a minimum expenditure of time and money.

In this direction the creative initiative of field personnel may contribute much, so as to permit proper use of the summer seasom for the fullest possible study of the magnetic field of the given locality, improvement of the accuracy of measurement of magnetic field intensity, close adherence of routes to the needs of the locality, and simplification and increased precision in elaboration and graphic presentation of the findings.

The ultimate object of all improvement in techniques and procedures in aerial magnetic survey is improvement in the geological effectiveness thereof. Study of the experience accumulated in the employment of aerial magnetic surveying for the solution of various geological problems is one of the necessary conditions for the attainment of positive results in this field. Analysis of the data of aerial magnetic survey for a given area requires complete employment of all the available geological data on the territory under investigation, materials and conclusions on work conducted by other geophysical methods and of data on the physical properties of the rocks of the given area. In addition explanation of the causes of changes observed in the magnetic field must also make use of mathematical methods of calculating the components constituting the magnetization of various bodies.

Only all-inclusive employment of the total geological and geophysical data on the district, with consideration of experience attained in work in other districts and with employment of methods of mathematical analysis, is capable of assuring the fullest utilization of the data obtained by aerial magnetic surveys to derive properly grounded geological conclusions and charts and thereby to accelerate and reduce the cost of solving problems involved in the search for new deposits of mineral resources.

CHAPTER I THE ANOMALOUS GEOMAGNETIC FIELD

1. The Relation of Magnetic Anomalies to Geological Structure

Experimental data on the size and direction of the magnetic field at the earth's surface has provided the basis for the creation of a theory which regards the intensity of the field at any geographic point as the geometric sum of the magnetic forces $T = T_0+T_1+T_2+T_3$, in which the primary member T_0 is the vector of the magnetic field of a uniformly magnetized sphere and the other 3 items are vectors of anomalous fields identified by area as continental (T_1), regional (T_2), and local (T_3). The boundary between the latter 2 is entirely a matter of convention. Regional anomalies include those whose areas is in the range of hundreds or thousands of square kilometers while local anomalies include all which are smaller than that.

There are various views as to the reasons for the existence of continental magnetic anomalies. Employing formal mathematical analysis, applied to rounded-off contours of continental anomalies, certain writers have concluded that their sources lie at very considerable depths, measurable in fractions of the earth's radius (cf. Kalinin, 1940). This view is given support by considerations arising from the study of certain other geophysical data (Kazanli, 1948).

One of the continental anomalies embraces the entire territory of Eastern Siberia. In evaluating the present theories as to the causes for this anomaly, it is impossible not to be attracted to the fact that the central portion of the anomaly corresponds to the area of the highly magnetic Siberian trap rock. This coincidence is hardly accidental and therefore the opinion of other workers (cf. Glebovskiy, 1946) who see a direct connection between the maximum in the Siberian magnetic field and special features of the geological structure of this district is worthy of serious attention. Convincing proof of the supposed connection between not only local and regional, but continental anomalies, with the solid crust of the earth would introduce important new elements into the general science of geomagnetism and would provide the basis for reexamination of such questions as the reason for the difference between the magnetic and the geographical poles.

The inadequate degree of study given to the magnetic field in areas of continental anomalies, the Siberian included, makes it impossible as yet to provide a convincing basis for the above hypothesis. Aerial magnetic surveying with simultaneous study of the physical properties of the rocks and the character of their magnetization would be of decisive importance in the study of these fields.

Certain remarks are in order as to the classification of anomalies as regional and local. This classification is entirely appropriate in a study of fields terrestrial or continental in scope, where the smaller fields appear in contours flattened out by the scale. However, when a magnetic field is studied with prospecting as the object, regional anomalies take on entirely new contours on the basis of large scale maps and reveal themselves to consist of number of larger and smaller anomalies. In toto they reflect the special regional features of the magnetic field, but no single anomaly taken individually may actually be termed regional in the sense that that word is understood by geologists.

Sometimes geophysical prospectors apply the term "regional anomaly" to anomalies over large massifs of magnetic rocks, which cannot be termed regions in geological terminology.

The terminology employed in prospecting geophysics must be brought into agreement with that of geology, so that in magnetic prospecting practice it is proper to speak of regional peculiarities in magnetic fields or of regional anomalies, the latter being taken to mean the totality of the various changes in a magnetic field which correspond to a particular geological region. As far as the identification of individual anomalies is concerned, only those determinations are of value which testify to the geological nature of the anomaly, as where it is a function of igneous rocks large or small in quantity, or of metamorphic layers, contact strata, products of tectonic destruction, etc.

From the viewpoint of ground-level surveys, the division of anomalies into "deep" and "superficial" would have some practical value. However in aerial surveys classification on this basis cannot be used because of the changing value of the major index.

Below we shall refrain from use of the terms "local" and "regional" anomalies in examining the results of aerial magnetic surveys, although in individual instances regional peculiarities of a magnetic field will be discussed.

At present there is no longer any doubt that magnetic anomalies (other than continental) are called forth by nonuniformities in the geological structure of the upper portion of the earth's solid crust. Experimental data obtained from study of the intensity of magnetization of mineral rocks and ores confirm the identity between observed and theoretical anomalies, calculated analytically on the basis of data as to the geological structure of particular areas and the intensity of magnetization of rocks constituting the area under study.

Certain instances of disagreement between the values practically arrived at and those theoretically calculated testify not to any doubt as to the general view of the causes of anomalies but to the inadequacy of the methods of comparison adopted.

Much statistical material has been accumulated on the susceptibility of mineral rocks and ores to magnetication. It has been established on the basis of this data that only materials containing ferromagnetic minerals, - magnetite, titanomagnetite, hematite, and pyrrhotite-, are capable of intensive magnetization. The presence of these minerals is always accompanied by an elevated capacity for magnetization in the earth's magnetic field. However no quantitative dependence of the magnetic susceptibility of rocks upon the relative content of ferromagnetic minerals in these rocks has been demonstrated.

Moreover investigation of various rocks containing much magnetite has demonstrated that the relative magnetite content is not the sole factor determining the degree of susceptibility to magnetization. There are other factors whose effect upon degree of magnetization is so great that rocks with a greater relative content of magnetite may be magnetized to a significantly lesser degree than rocks with a lesser magnetite content. This is apparently related to whether the ferromagnetic minerals are present in the given rock as inclusions or as a cementing medium. However there apparently are also other factors, not yet determined, which significantly affect the degree of magnetic susceptibility of rocks containing ferromagnetic minerals, as the degree of magnetization of one and the same rock, measured by various specimens, varies within considerably wider boundaries than the relative content of ferromagnetic minerals.

Still less study has been given to the question of residual magnetization of rocks, which in many cases exercises a decisive effect on the intensity of magnetic anomalies. Residual magnetization sometimes attains magnitudes exceeding the contemporary magnetic field 10 fold or more, while the magnitude and direction of the vector or residual magnetization varies widely from specimen to specimen of the identical rock.

Residual magnetization of rocks is widespread in nature. Adequate evidence has been found to support the hypothesis that rocks subjected to high temperatures have passed, in cooling, through the Curie point at which magnetic susceptibility in a weak earth field was considerably higher than that which this rock demonstrates at relatively low temperature. If the rock possesses coercive force (and research has shown this property to be possessed by mineral rock to a high degree), residual magnetization will develop and be preserved. The uneven cooling of rocks from point to point within the mass may be explained by the observed fact of marked changes in the vector of residual magnetization in various specimens of the same rock.

In addition to the minerals listed, many other rock-forming minerals possess magnetic susceptibility to a degree that rocks formed with their participation are capable of creating magnetic anomalies fully capable of measurement. Minerals in this category include hornblende, biotite, serpentine, etc. The few studies that have been made of the magnetic susceptibility of minerals testify to marked fluctuations in the susceptibility of one and the same mineral. For serpentine, for example, the following data have been adduced: 10; 250; $1,300 \times 10^{-6}$. The question as to the presence or absence of residual magnetization in rock-forming minerals has not been studied at all if we omit isolated data testifying to the possibly significant role thereof in the total intensity vector (cf. Logachev, 1951).

Among the most widely distributed minerals, quartz and certain others not found as universally are practically nonmagnetic, meaning that they are incapable of creating measurable magnetic anomalies.

The virtually nonmagnetic rocks include the majority of the sedimentaries (limestones, dolomites, marls, gypsum, rock salt), many metamorphic rocks (quartzites, marble, most of the gneisses) and certain igneous rocks (most of the granites and quartz porphyries). As far as the remaining types of rock are concerned, we can only draw the general conclusion that in the sedimentary complex there are differences among the clays and sandstones which set up distinctly measurable anomalies (dependent upon admixtures present). In the metamorphic complex one may encounter varieties of hornstone and shale with very high intensities of magnetization (that is, magnetite shales), while among the igneous rocks one encounters a range from the practically non-magnetic to others with a high magnetite content with the very highest level of magnetic susceptibility. As far as the igneous rocks are concerned, it is correct to say that the most highly magnetized are the basic and ultrabasic rocks (basalts, peridotites, and serpentines).

The relationship between the intensity of magnetization of mineral rocks and their composition, structure, and geological history governs the broad range of variation in their intensities and consequently the special features of magnetic anomalies discovered on the ground or from the air. This expands the possibilities inherent in magnetic surveying when used for geological mapping and prospecting for minerals.

On the other hand the complex relationship between the intensity of rock magnetization and various other factors to which very little study has been given gives rise to doubt as to the possibility of deriving geological conclusions from anomalous magnetic fields. This is particularly true when the data of magnetic surveys are studied in isolation from the concrete geological environment and the work is based solely on statistical data on the magnetic properties of specific categories of rocks.

The spatial distribution and intensity of anomalous magnetic fields due to mineral rocks have been studied over large areas and for various rock complexes, both on large and small scale. The experience accumulated in magnetic survey and the geological data on the territories under investigation have established relationships between magnetic fields and geological structure which may be employed in future investigations. The accumulated experience in magnetic survey and the data obtained by other methods of geophysics, the use of conclusions from the theory of the magnetic field of magnetized bodies and experimental data on the intensities of rocks in the area under study, calculation of the components of the stratification and intensity of magnetization, and analysis of the geological data taken together provide an idea as to the geological structure of the territory under study, subsequently rendered more precise either by means of other methods of geophysics or by excavation.

Aerial magnetic surveys are now employed to search for deposits of highly magnetic iron ores, for geological charting in connection with gas and oil prospecting, and to seek nonferrous metals that may be encountered in fault zones, contact zones between basic and ultrabasic massifs, and in geological research undertaken in conjunction with major hydrological engineering projects. Experience has shown that maps of the magnetic field compiled on the data of aerial magnetic survey provide valuable data for giving precision to geological maps on the same scale and consequently for more confident isolation of areas offering hopes of finding particular resource minerals. Doubtless the further perfection of the methods of geological interpretation of the anomalous magnetic field will expand the scope of the problems to be resolved by means of aerial magnetic survey.

2. The Z_a and ΔT Magnetic Fields and Their Interrelation

In practical aerial magnetic surveying 2 types of instruments are in most general use, the Z aeromagnetometer, which performs continuous measurement of the vertical component of the geomagnetic field, and the T aeromagnetometer, which performs continuous measurement of changes in the magnitude of the complete T vector irrespective of change in direction.

Magnetic surveys made at the earth's surface are usually limited to measurement of Za and, more rarely, Ha (or ΔH). Therefore the methods of mathematical analysis of fields have been developed primarily in terms of the Za field. It is natural that when the first aerial magnetometers were designed effort was concentrated on developing an instrument which would facilitate the fullest utilization of the theory and the rich experience developed in terms of work done on the ground. However it did not prove possible to create a high precision Z aeromagnetometer because in order for the Z field to be measured to adequate accuracy the measuring element had to be levelled to an increased degree of perfection while this was not the case in measuring ΔT.

Consequently in measuring increase in the total vector or its component the measuring element must be oriented to the vector in some specific fashion. For example if permalloy rods are used, they must be oriented in the direction of the vector being measured. When the total T vector is measured the error in setting the rod at an angle, α, results in a reduction in the acting force by the magnitude $T-T\cos\alpha = T(1-\cos\alpha) = T \cdot 2\sin^2\frac{\alpha}{2}$. If we assume that $T = 50{,}000\,\gamma$, and $\alpha = 1^\circ$, the error of measurement will be about $8\,\gamma$. We will obtain another result if we measure Z and orient the measuring element by the direction of Z vector. If the measuring element shows an inclination of α, the force of Z will change, and an additional force, $H\sin\alpha$ will appear, so that the effective force will be $Z\cos\alpha \pm H\sin\alpha$. The last term is so large that the change, $Z(1-\cos\alpha)$, occurring in Z may be ignored. Assuming $\alpha = 1^\circ$ and $H = 15{,}000\,\gamma$, we obtain an error of measurement of the order of $250\,\gamma$.

Thus if the condition be set that the error in measurement due to deviation in the measuring element from the given direction in both instruments not exceed, for example, $2\,\gamma$ in either direction, the instrument for measuring ΔT must hold its orientation to an accuracy of 15' in either direction, and the instrument for measuring Za must hold its orientation to an accuracy of 0'.5. This means that the measuring component must meet requirements 30 times as rigid in the vertical position than in measurement of ΔT. The difficulties encountered in assuring this level of accuracy when a measuring element for Z is mounted in a moving aircraft has required that measurement of Z be dispensed with in favor of measurement of ΔT.

In this connection the question presented itself as to the development of a theory with the aid of which it would be possible to use the measured values of Δ T to calculate the depth, dimensions, shapes, and position in space of magnetized bodies in a manner analogous to that done with regard to the Z field. However a study of this question led to the conclusion that no special theory for the ΔT field was needed, as the results of measurements taken from aircraft proved in almost every instance to be capable of being handled completely under the theory developed for the Za field in indirect magnetization.

The value of Δ T was determined as follows:

$$\Delta T = \sqrt{(Z_o + Z_a)^2 + (\vec{H}_o + \vec{H}_a)^2} - T_o =$$
$$= \sqrt{T_o^2 + 2Z_oZ_a + 2H_oH_a \cos A + T_a^2} - T_0 =$$
$$= T_o \left[\sqrt{1 + 2\left(\frac{Z_a}{T_o}\sin i + \frac{H_a}{T_o}\cos i \cos A\right) + \left(\frac{T_a}{T_o}\right)^2} - 1 \right], \quad (2,1)$$

in which t is the angle of inclination of the T vector; A is the magnetic azimuth of the Ha vector; while the other symbols are the standard designations for normal and anomalous components of the geomagnetic field; and T is the total vector, Z is the vertical, and H the horizontal component of the geomagnetic field. The subscript "o" indicates that a normal component is involved and "a" an anomalous one is involved.

When the value of T_a is small the second term under the radical is of a magnitude considerably smaller than unity, while the third is a second-order small number. Ignoring the latter and applying the formula for analysis of binomial to the rest, we obtain

$$\Delta T = Z_a \sin i + H_a \cos i \cos A. \qquad (2,2)$$

If the small terms of the second order be taken into account, analysis of the binomial gives us:

$$\Delta T_2 = \Delta T_1 + \frac{1}{2}\frac{1}{T_0}(T_a^2 - \Delta T_1^2), \qquad (2,3)$$

in which ΔT_1 represents a first approximation for equation (2.2).

Where small anomalies are concerned, consideration of members consisting of second-order small numbers does not affect the value of ΔT, calculated by equation (2.2). Actually, if the anomaly at the given point $T_1 < 1000\,\gamma$, then when $T_0 = 0.5$ e the correction will be less than $10\,\gamma$, as ΔT_1^2 is always a positive number.

The differential $T_a^2 - \Delta T_1^2$, upon which the magnitude of the correction is dependent, is expressed in its general form by the equation:

$$T_a^2 - \Delta T_1^2 = Z_a^2 \cos^2 i + H_a^2(1 - \cos^2 i \cos^2 A) - Z_a H_a \sin 2i \cos A.$$

Given the shape and area of the body, one may calculate the value of the correction and be confident that employment of equation (2.2) is permissible within wide limits in which the changes in ΔT are expressed in thousands of gammas. In aerial surveying an anomaly approximating 0.1 e in intensity is a rare exception, so that the approximated formula (2.2) is applicable for all practical purposes to virtually all results of aerial survey by the T aeromagnetometer.

The relative value of the correction, p, for each point taken individually appears as follows

$$p = \frac{1}{2T_0} \frac{T_a^2 - \Delta T_1^2}{\Delta T_1}.$$

As ΔT_1 may take on values of infinitely small size, determination in relative numbers of the corrective term in the ordinate of the curve is meaningless.

Equation (2.1) may also be presented in another form:

$$\Delta T = \sqrt{T_0^2 + 2T_0 T_a \cos\beta + T_a^2} - T_0,$$

in which β is the angle between T_o and T_a.

Applying to this expression the same analytic equation, and restricting ourselves to terms comprising small numbers of the first order, we obtain

$$\Delta T = T_a \cos\beta, \qquad (2,4)$$

that is, to a first approximation ΔT equals a projection of Ta in the direction of the total vector for the normal field, T_o.

Expressions (2.4) and (2.2) are determined by one and the same geometric magnitude, as may be seen in Figure 1.

Figure 2 shows the change ΔT over a vertical stratum in a case of vertical magnetization relative to the azimuth of the extent of the stratum in correspondence with formula (2.2).

It is easy to see that equation (2.2) is identical in appearance with the expression determining Za over a body with inclined magnetization and is distinguished therefrom by a constant factor which is nearly unity, and is $\frac{I_z}{I_o} = \sin i$, where I_o is the total vector of the intensity of magnetization, I_z is its component along axis z, and i is the angle of inclination.

Let us demonstrate this for a 2-dimensional situation, that is, where the body extends into the infinite distance. We determine the direction by means of the magnetic azimuth, A'. In this instance the vectors Ha will be directed along azimuths A, differing from A' by 90°. Let the y axis follow the direction of the body. The components of the total vector of intensity of magnetization, I_0, will be:

$$I_x = I_0 \cos i \sin A' = I_0 \cos i \cos A; \quad I_z = I_0 \sin i.$$

Now let us write the values for H'a and Z'a in oblique magnetization, expressed by the potential of gravity in according with Poisson's theorem:

$$H'_a = I_0 \cos i \cos A \frac{\partial^2 V}{\partial x^2} + I_0 \sin i \frac{\partial^2 V}{\partial x \partial z};$$

$$Z'_a = I_0 \cos i \cos A \frac{\partial^2 V}{\partial x \partial z} + I_0 \sin i \frac{\partial^2 V}{\partial z^2}.$$

With direct magnetization, when $I_x = 0$, we obtain

$$H_a = I_0 \sin i \frac{\partial^2 V}{\partial x \partial z}; \quad Z_a = I_0 \sin i \frac{\partial^2 V}{\partial z^2},$$

from which we derive

$$\frac{\partial^2 V}{\partial x \partial z} = \frac{H_a}{I_0 \sin i}; \quad \frac{\partial^2 V}{\partial z^2} = \frac{Z_a}{I_0 \sin i}.$$

Writing these values into expressions Ha' and Za', and bearing in mind that for a 2-dimensional problem

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial z^2} = 0,$$

we obtain

$$H'_a \sin i = -Z_a \cos i \cos A + H_a \sin i;$$

$$Z'_a \sin i = Z_a \sin i + H_a \cos i \cos A. \qquad (2,5)$$

Comparing expressions (2.2) and (2.5) we find that ΔT is expressed analytically in the same manner as Za in oblique magnetization.

Establishment of this fact relieves us of the necessity to develop a special theory for the field of ΔT and permits utilization of the theory developed for the Z field in oblique magnetization, corresponding to the direction of the magnetizing terrestrial field.

Limits to the foregoing appear only in cases in which the intensity of the anomaly, ΔT, is expressed in many thousands of gammas, approximating tenths of an oersted. In this case equation (2.2) becomes a rough approximation. Correspondingly the elements of stratification of magnetized bodies may also be taken as merely an approximation. The relationship between field ΔT and Za expressed by equation (2.5) may also be accepted as an approximation where triaxial bodies are concerned.

By way of confirming the applicability to the ΔT field of the known methods of employing the Za field to calculate elements of stratification, it is in place to recall that in the practice of magnetic survey, when calculating elements of stratification in the measured field Za, we almost always make the assumption that bodies creating anomalies are magnetized vertically, while in reality vertical magnetization is a special and rather rare case. On the same basis this assumption may be employed in practice when using the ΔT field.

However the current theory developed to calculate the elements of stratification of magnetized bodies by the measured field (and by the ΔT field) makes it possible in certain cases to allow for oblique magnetization and to increase the accuracy of the solutions accordingly. Consequently in geological interpretation of magnetic anomalies, whatever the component by which the latter are represented, it is necessary to allow for the inclined position of the vector of the magnetizing field and to render the decisions arrived at more precise if the influence of oblique magnetization is significant.

The established connection between field ΔT and field Za, which holds satisfactorily for virtually all the results of aerial magnetic survey by means of the T aeromagnetometer, permits us to proceed below to set forth the theoretical portion of the present handbook relative to the Za field without having to specify in each case that the conclusions are equally applicable to the ΔT field.

3. The Analytical Connection between Fields Za and Ha and Calculation of Ha on a Given Za Field

In magnetic surveying practice the horizontal component Ha is sometimes measured only during work above ground, while in calculating the depth and dimensions of magnetized bodies it is useful in some cases to be familiar not only with the Z or ΔT field but with the distribution of the horizontal component.

The question of the calculation of H in accordance with a given distribution of the Z field over a plane was dealt with in detail by I. N. Pudovkin (1950). His work presents a tabular form of calculating H for a 2-dimensional problem. Here we offer a simpler derivation of the analytical expression of H through a given value of the Z or ΔT field and a nomographic method of calculating H both for 2-dimensional and 3-dimensional problems. The method of calculation proposed requires very little work compared to the tabular method.

The derivation of the formulas is based on the hypothesis that the Z field given for a certain surface area is created not by bodies actually in existence but by fictitious magnetic masses distributed over this surface in accordance with a variable density σ_1.

We know that the Z field over a magnetized body occupying the halfspace is expressed by the formula $Z = 2\pi\sigma$, in which σ is a magnitude called the "surface density of magnetism." In practice this formula holds if the angle of visibility of the surface of the body from the observation point in any vertical section is π. If the point of observation lies on a surface coinciding with the surface of distribution of the magnetic masses, this condition is fulfilled. Consequently on the basis of the hypothesis that at each individual point at the surface of measurement the magnitude of Z_i is a function of the presence of magnetic masses with a surface density of σ_i, it follows that

$$\sigma_i = \frac{Z_i}{2\pi}.$$

Thus we replace the body actually existing and causing the anomaly by the assumption of a variable magnetic density σ_i at the surface of measurement, determined at each point by the equation indicated above.

Let us begin by examining the 2-dimensional problem, that is, an instance in which the distribution of the Z field is given along the x axis, the direction of which is normal to the long axis of a highly elongated body.

Employing the familiar expression for the horizontal component over the pole function

$$H = 2\sigma \frac{x}{h^2 + x^2},$$

we write the expression dH from the element dx with the fictitious surface of density $\sigma = \frac{Z}{2\pi}$, with allowance for the fact that h = 0, as the value dH is calculated at points along the x axis:

$$dH = \frac{Z}{\pi(x - x')}\,dx \qquad (3,1)$$

Here x represents the abscissa of element dx, while x' represents the abscissa of point P, at which dH is calculated.

The full value of H, based on all the fictitious magnetic masses on the x axis, will be

$$H(P)=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{z}{x-x'}dx. \qquad (3,2)$$

For convenience of calculation let us shift the starting point of the coordinates to point P at which H(P) is calculated, or in other words let us assume that $x' = 0$. Then we obtain

$$H(P)=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{Z}{x}dx. \qquad (3,3)$$

We find the integral in the following manner:

$$H(P)=\frac{1}{\pi}\int_{-\Delta x}^{\Delta x}\frac{Z}{x}dx+\frac{1}{\pi}\left[\int_{-\infty}^{-\Delta x}\frac{Z}{x}dx+\int_{\Delta x}^{\infty}\frac{Z}{x}dx\right]. \qquad (3,4)$$

Bearing in mind the fact that

$$\int_{-\Delta x}^{\Delta x}\frac{Z}{x}dx\approx\frac{Z(\Delta x)-Z(-\Delta x)}{\Delta x}\Delta x,$$

and that

$$Z(\Delta x)-Z(-\Delta x)=\Delta Z(P),$$

or in other words the increase in field Z between $-\Delta x$ and Δx, we obtain:

$$H(P)=\frac{1}{\pi}\Delta Z(P)+\frac{1}{\pi}\left[\int_{-\infty}^{-\Delta x}\frac{Z}{x}dx+\int_{\Delta x}^{\infty}\frac{Z}{x}dx\right]. \qquad (3,5)$$

Let us note that

$$\int_{x_m}^{x_{m+1}}\frac{dx}{x}=\ln\frac{x_{m+1}}{x_m}. \qquad (3,6)$$

Now let us mark off segments equivalent to Δx on axis x, to the right and left of the origin of the coordinates, Δx being an arbitrarily chosen unit. Now let us plot off in both directions from the origin of the coordinates, points at a distance x_m, of such a nature that expression (3.6) is represented by a constant, termed c. In each interval between x_m and x_{m+1}, let us take for the true value of Z its average value, equal to Z_i. Then, instead of expression (3.5), we will have:

$$H(P)=\frac{1}{\pi}\Delta Z(P)+\frac{c}{\pi}\left[-\Sigma Z_{-i}+\Sigma Z_{+i}\right]. \qquad (3,7)$$

Here the signs of the subscript i signify that the first total includes all the values of Z_1 to the left of point P and the second all the values to the right of that point.

Now let us take the value of c to be such that the coefficient before $\sum$ will be, for example, 0.1, so that c = 0.1 π = 0.314. Thus we obtain

$$\frac{x_{m+1}}{x_m} = e^{0,314} = 1,368,$$

or in other words the distances x_i increase in geometric progression, the denominator being q = 1.368. Consequently the distances will be 1, 1.37, 1.87, 2.56, 3.51, 4.80, 6.57, 8.98, 12.3, 16.8, 23.0, etc.

We use translucent paper to plot our scale. We select our initial distance Δx = 1 in terms of the scale of the Z curves on which we will calculate the H curves. Thus we may plot a scale in which $\Delta x = \pm$ 2.5 mm – Δx = 5 mm (Figure 3). All other points are determined by distance increasing in geometric progression.

To determine ΔZ and the average values of Z_i, a horizontal grid is plotted on the same transparent paper in accordance with the scale and amplitude of the Z curves employed.

In the calculations attention must be given to the signs of the magnitudes entering into equation (3.7). Be it noted that the value of c is negative as we proceed leftward from the starting point of the scale and positive as we move to the right. Therefore the first sum in equation (3.7) is shown with a minus sign due to the fact that c is outside the brackets. The sign of Δz is determined by algebraic subtraction $Z(+\Delta x)-Z(-\Delta x)$. The sign of each separate value of Z_i corresponds to the sign of the average ordinate of the curve on the drawing. If the given curve Z does not enter into the normal field, it is extrapolated graphically to the value Z = 0.

The accuracy to which the H curve is calculated on the data of the Z curve depends upon the intervals of approximated integration. The smaller the value of Δx, the greater the accuracy of the curve calculated. The accuracy of the derivation is limited only by the error in the initial data on the distribution of the Z field.

Let us clarify the adoption of this method in practice. Figure 4 shows the Z curve as it runs normal to the long axis of the anomaly as determined by surveys via a number of courses. In order to calculate H at point P we plot the grid so that the central line passes through point P and the horizontal lines are parallel to the zero point of the graph. Now we enter the values for ΔZ and the mean values for Z_i in the intervals of the grid. On the original (the scale of the drawing has been reduced for purposes of reproduction herein) $\Delta Z(P) = 14$ mm. Correspondingly the Z_i values at the intervals on the grid to the right of point P are respectively $15+18+23+29+32+27+18+17+5-1-1 = 182$. In the intervals to the left of point P we obtain accordingly $-2-3-4-4-3.5-2.5-1.5-0.5+0 = -21$. The latter sum is subtracted algebraically from the first, so that we obtain as a result

$$H(P) = \frac{1}{\pi} 14 + 0{,}1\,(182 + 21) = 24{,}8 \text{ мм}.$$

A 3-dimensional problem undergoes solution in analogous fashion. Let us assume that the problem is to calculate H at point P on a plane where the value of Z is known at any given point. In this case we may assume an imaginary magnetic density $\sigma = \frac{Z}{2\pi}$ at an arbitrarily chosen element ds, where the vertical component is Z. The horizontal component H, created by a unipolar anomaly, is expressed by the familiar formula:

$$H = \frac{mx}{(h^2 + x^2)^{3/2}}.$$

In the given instance $h = 0,\ m = \frac{Z}{2\pi}\ ds,\ ds = r dr d\theta.$ Let us designate the horizontal component from element ds by the symbol dH. Writing in the values indicated above, we emerge with

$$dH = \frac{Z}{2\pi} \cdot \frac{dr}{r} d\theta.$$

Let us break dH into its components along the axes of a rectangular system of coordinates in which x faces northward, and y to the east. Thus we obtain:

$$dH_x = \frac{Z}{2\pi} \frac{dr}{r} \cos\theta \, d\theta,$$

$$dH_y = \frac{Z}{2\pi} \frac{dr}{r} \sin\theta \, d\theta.$$

Let us divide the entire area into spaces of equal effect, within which we shall consider the Z values to be constant and equal to the average value of Z_i for each space. For example let us present:

$$\Delta H_x = \frac{Z_i}{2\pi} \int_{r_m}^{r_{m+1}} \frac{dr}{r} \int_{\theta_n}^{\theta_{n+1}} \cos\theta \, d\theta = 0{,}01 Z_i.$$

Integrating, we find

$$\Delta H_x = \frac{Z_i}{2\pi} \ln \frac{r_{m+1}}{r_m} (\sin\theta_{n+1} - \sin\theta_n) = 0{,}01 Z_i.$$

Assuming the difference in sines to be a constant, for example:

$$\sin\theta_{n+1} - \sin\theta_n = 0{,}2,$$

we find

$$\ln \frac{r_{m+1}}{r_m} = 0{,}314,$$

from which we get

$$\frac{r_{m+1}}{r_m} = 1{,}368.$$

Let us plot our graph as follows. In accordance with the given values of θ we draw vector radii from the x axis and at θ angle, which is equivalent successively to 0; 11°,7; 23°,6; 36°,9; 53°,2; 90°,0; 126°,8; 143°,1; 156°,4; 168°,3; 180° , etc. (In 2 of the quarters of the circle the vector radii are continuations of the vector radii drawn in the first 2). Now we draw circles of radii r_m, equivalent to 1, 1.37, 1.87, etc, in geometric progression, the denominator q being 1.368 (Figure 5).

It is clear that each space, limited by the 2 neighboring arcs and radii, will represent the elementary expression $\Delta H_x = 0.01Z_1$.

It remains for us to calculate the elementary value of $\Delta H'_x$ from the imaginary magnetic mass distributed within a circle the radius of which is r = 1, or

$$\Delta H_x' = \frac{1}{2\pi}\int_0^{r=1} Z\frac{dr}{r}\int_0^{2\pi}\cos\theta\, d\theta.$$

In accordance with the prior derivation,

$$\int_0^{r=1} Z\frac{dr}{r} \approx \Delta Z,$$

that is, the increment in Z in the interval from the center of the grid to the first circle. In practice it is more convenient to derive the magnitude of increment from the drawing of the anomaly, employing the full diameter. In view of the fact that the entire area has been broken down into sectors we may write:

$$\Delta H_x' = \frac{0{,}2}{2\pi}\Sigma\Delta Z = 0{,}032\Sigma\Delta Z,$$

in which $\sum \Delta Z$ represents the sum of the increments in all sectors.

The grid we have thus prepared is made use of as follows. On the chart showing the Z field as isolines, or the numerical values at determinate points, we note the points at which the value of H is to be calculated. The grid plotted on transparent paper is placed over the chart in such fashion as to cause its center to correspond with the point for which it is desired to calculate H, while the x axis is set along a given coordinate axis, such as the astronomic meridian. For each space formed by the intersection of radii and circles we determine the average value of Z_i with its sign. Then we calculate the total Z_i sum, observing the condition that all the values in the 2 upper quarters of the circle be given signs opposite to those for the quarters whose radii have been extended into them. The ΔZ increment is determined, with its corresponding signs, along 10 diameters of a circle with radius $r = 1$, in directions corresponding to the position of the bisectrix of each angle. The direction from the lower to the upper quarters of the circle is taken as the positive direction of the bisectrix. Thus we obtain:

$$H_x = 0{,}032\Sigma\Delta Z + 0{,}01\Sigma Z_i.$$

In order to calculate H_y the grid is rotated 90^o clockwise on its center, whereupon $\sum\Delta Z$ and $\sum Z_i$ are calculated, employing the signs shown on the grid. When this process of rotation is employed the signs of the 2 right hand quarters of the circle are retained in performing the addition and those in the 2 left hand quarters are reversed. In determining the sign of the gradient along each diameter the positive direction is taken to be that from the left to the right quarters of the circle. The full H vectors are plotted on the values of H_x and H_y as derived.

In practical calculation considerable simplification is permissible in the calculations. Thus in areas of rather uniform fields it is permissible to determine the average value of Z_i not for each space taken separately but for a group thereof. In this connection we must not forget that the Z_i value found in this manner must be increased by a factor equal to the number of spaces found in the given group.

Let us illustrate the procedure for calculation by an example. In Figure 6 the Z field is shown by isolines drawn at intervals of 25 γ. In order to calculate H at point P let us plot our grid in such fashion that its center coincides with point P and the x axis corresponds to the direction of the astronomical meridium. Let us start by calculating $\sum\Delta Z$. Proceeding by sectors from left to right, beginning with the horizontal line, the approximate increases in ΔZ will be $-5+0+5+10+20+20+25+30+30+20=155\,\gamma$, from which we find the first term to be $0{,}032 \cdot 155 \approx 5\,\gamma$.

Let us calculate the second term. Within each ring we may write average Z_i values for each point but we may also take a group of spaces with identical average values.

In the first ring we obtain within the 2 upper quarters of the circle from left to right $50+3 \cdot 60+6 \cdot 70=650$, while in the 2 lower quarters we obtain $3 \cdot 50+7 \cdot 40=430$ so that the first ring as a whole gives us $650-430=220$.

In the second ring we have $3 \cdot 50+3 \cdot 70+3 \cdot 85+70-3 \cdot 50-7 \cdot 40=255$.

In the third ring $35+3 \cdot 50+2 \cdot 90+85+110+90+65-3 \cdot 40-7 \cdot 35=350$.

In the fourth ring $2 \cdot 30+3 \cdot 50+70+75+120+125+70-4 \cdot 30-6 \cdot 25=400$.

In the fifth ring $3 \cdot 0+3 \cdot 25+40+70+120+60-2 \cdot 30-8 \cdot 15=185$.

In the sixth ring $-25-4 \cdot 30-25+0+40+70+40-2 \cdot 20-8 \cdot 10=-140$.

In the seventh ring $-30-4 \cdot 40-2 \cdot 25+10+40+10=-180$.

In the eighth ring $-6 \cdot 10+10-25=-75$.

The second term is $0{,}01\,\Sigma Z_i \approx 10\,\gamma$ and consequently $H_x \approx 15\,\gamma$.

After the grid has been turned 90° let us calculate H_y in the same fashion. It proves to be 25γ. Let us enter at point P the components H_x and H_y on which the H vector may now be plotted.

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4. Changes in the Intensity of the Geomagnetic Field with Increase in Altitude of the Plane of Observation

The intensity of the geomagnetic field at each geographic point is the geometric sum of magnetic forces from various sources, the vector of homogeneous magnetization of the globe, the vector of so-called "continental anomalies," and the vectors of anomalies, the sources of which are magnetized rocks and ores. In order to determine the change in the intensity of the geomagnetic field in relation to the height of the observation point, it is necessary to examine the effect of change in attitude upon the field of each source taken individually.

The vertical gradient of the earth's field of uniform magnetization may be calculated from the fundamental equations determining the intensity of the field on a spherical surface of r radius, in the center of which one finds a magnet of infinitesmal size, the magnetic moment of which is M. We know that the intensity of the H_r field in the direction of the vector radius r, connecting a given point P with the center of the magnet, and the intensity of field H_θ in a direction normal to H_r are expressed by the formulas:

$$H_r=\frac{2M}{r^3}\cos\theta;\quad H_\theta=\frac{M}{r^3}\sin\theta, \qquad (4.1)$$

in which θ is the angle between the axis of the infinitesmal magnet and direction r (the prologation of point P to the magnetic latitude).

In the standard designations of the elements of the geomagnetic field, $H_r=Z,\ H_\theta=H.$

From equation (4.1) we obtain

$$\frac{\partial Z}{\partial r}=-3\,\frac{2M}{r^4}\cos\theta;\quad \frac{\partial H}{\partial r}=-3\,\frac{M}{r^4}\sin\theta.$$

The magnitude of the vertical gradient varies in the various latitudes. Thus if in the western portion of the USSR at a latitude of about 60° we take $Z = 0.50$ э, $H = 0.15$ э, then given $r = 6{,}400$ Km, the gradients will be

$$\frac{\partial Z}{\partial r} = -20\gamma/\text{км}; \quad \frac{\partial H}{\partial r} = -7\gamma/\text{км}.$$

No experimental determination of the vertical gradient of the field of uniform magnetization has been made.

There is no data whatever on the vertical gradient of continental anomalies. It is impossible to derive them theoretically by means of the analytical expression, as the causes for the appearance of these anomalies have not been discovered. Calculation on the basis of LaPlace's equation

$$\frac{\partial Z}{\partial z} = -\left(\frac{\partial X}{\partial x} + \frac{\partial Y}{\partial y}\right) \qquad (4.2)$$

is impossible because continental anomalies have not been studied sufficiently.

When mineral prospecting employs magnetic survey at the earth's surface or from the air on any scale the fields of uniform magnification and continental anomalies are excluded so that the result will show only the field created by geological features. In aerial surveying, carried out approximately at the same level from the earth's surface, the vertical field gradient $T_0 + T_1$ does not affect determination of the anomalous magnetic field. When high accuracy measurements are made at different altitudes from the earth's surface hundreds of meters apart data on the vertical gradient of the $T_0 + T_1$ field may prove essential for purposes of proper calculation of magnetic anomalies arising due to the lack of uniformity in geological structure.

The lack of experimental data on this matter for the territory of the USSR and the experience acquired in eliminating the effect of the vertical field gradient T_0+T_1 on the results of measurements of magnetic anomalies at various altitudes make it necessary to guide ourselves by theoretical calculations of the T_0 field gradient for the given locality in accordance with the formulas adduced above derived from equation (4.1) and where the East Siberian continental anomaly is concerned from equation (4.2) applied to a schematic map of that anomaly.

Where aeromagnetic prospecting is used the matter of greatest interest is investigation of changes occurring with changing altitude in the distribution and intensity of anomalous magnetic fields as a result of inhomogeneities in geologic structure, that is, in those anomalies which are designated as T_2 and T_3 in the general formula for the geomagnetic field.

The analytical expression for the intensity of the magnetic field changes with change in the shape of the magnetized body, as is evident for instance from examination of the analytical expressions for curves Z and H over such bodies as a ball, vertical and horizontal cylinders, etc. As a result the necessity arises to examine the question as to the vertical gradient of the intensity of fields over bodies of various forms, with limitation solely to bodies of the simplest forms.

The vertical component of the magnetic field of a ball that has undergone vertical magnetization upon a line passing through the epicenter of the ball is expressed by the equation

$$Z=\frac{M(2h^2-x^2)}{(h^2+x^2)^{5/2}}, \tag{4,3}$$

in which M is the magnetic moment of the ball and h is the distance from its center to the plane of measurement. In its general form the vertical gradient Z is determined at any given point x by the equation

$$\frac{\partial Z}{\partial h} = \frac{3Mh\,(3x^2 - 2h^2)}{(h^2 + x^2)^{7/2}} \qquad (4,4)$$

From the equation $3x^2 - 2h^2 = 0$ we find $x = \pm 0,8h$. From the latter equation and equation (4.4) we see that as altitude increases the Z component in the central portion, determined by the distance ±0.8h from the starting points of the coordinates, declines, while it increases beyond the limits of the given value for x. The Z maximum declines in reverse proportion to the distance h raised to the third power.

The magnetic field of a body of vertical course may be treated in the same fashion as that of a bar magnet, in which the distance between poles is 2 l. We know that the field of such a magnet takes on the following appearance in the direction of the axis of magnification

$$Z = \frac{2M}{h^3}\left(1 + 2\frac{l^2}{h^2} + 3\frac{l^4}{r^4} + \ldots\right).$$

Limiting accuracy to 5%, we may assert that in a horizontal plane, the distance of which from the center of the object under study is 3 times as great as the vertical dimensions of the body, the magnetic field of the latter may be taken to coincide with that of the ball. We know that this fact is employed widely in calculating the magnetic field of a bar magnet on the formula $H = \frac{2M}{3}$, although this formula is valid for an infinitesmal magnet or a ball.

Thus the magnetic field of a body the linear dimensions of which are similar on all 3 axes, changes above the earth's surface in approximately the same fashion as does the field of a ball. The field of a body heavily elongated in the vertical changes in accordance with the same law, beginning at an altitude double or treble the vertical dimensions of the body.

The magnetic field of a horizontal cylinder of great length, vertically magnetized, is expressed along a horizontal line normal to the long axis of the body, as shown in the formula

$$Z = 2M\frac{h^2 - x^2}{(h^2 + x^2)^2}, \qquad (4,5)$$

in which M is the magnetic moment of a disc cut from this cylinder, the generatrix of the disc being equal to one unit of length, and h is the distance from the cylinder axis to the plane of observation. The coordinates meet at the point of intersection of the projection of the cylinder axis on the plane of observation and the axis x.

The gradient of the Z field along the vertical takes on the following appearance

$$\frac{\partial Z}{\partial h} = \frac{4Mh\,(3x^2 - h^2)}{(h^2 + x^2)^3}. \qquad (4,6)$$

From this it follows that in the midportion, within the limits of variation $x = \pm 0.6h$, the Z curve declines, but that outside these limits it increases. Z_{max} declines in inverse proportion to h raised to the second power.

It may readily be demonstrated that the field of highly elongated bodies of elliptical section and vertical long axis will at a given altitude be indistinguishable from the field of a cylinder, if the altitude of the aircraft be several times higher than the dimensions of sections taken through the vertical.

The field of a vertical stratum 2b thick, of very great length and depth, is expressed by the following formula for a line x transverse to the long axis:

$$Z = 2I\left[\operatorname{arc\,tg}\frac{x+b}{h} - \operatorname{arc\,tg}\frac{x-b}{h}\right], \qquad (4,7)$$

in which h is the distance from the upper edge of the deposit to the plane of observation and I is the intensity of magnetization.

The vertical gradient Z, given $2b \ll h$, will be

$$\frac{\partial Z}{\partial h} = -2I2b\frac{h^2 - x^2}{(h^2 + x^2)^2}. \qquad (4,8)$$

The ordinates of curve (4.8) differ from those of (4.5) only by a constant factor. In the interval $x = \pm h$ the value of Z declines with rising altitude while beyond this value it increases. Z_{max} declines in inverse proportion to h to the first power.

If the thickness of the body 2b is commensurable with its height h, then

$$\frac{\partial Z}{\partial h} = -2I\left[\frac{x+b}{h^2 + (x+b)^2} - \frac{x-b}{h^2 + (x-b)^2}\right]. \qquad (4,9)$$

Expression (4.9) has a form identical with that of expression Z over a horizontal thin layer of great extent, the horizontal dimensions of which are 2b. A constant factor provides the only difference between them.

The similarity of the curves is readily explained. A change in altitude by Δh is equivalent to vertical displacement of the body in the reverse direction. The problem is to find the difference in fields between the fields of the given and the displaced bodies or in other words to find the field of a body constituting the difference between the given and displaced bodies. In the former case, assuming 2b to be small, the difference between the 2 figures will in cross-section be of small dimensions along the x axis, and a small Δh along the z. We know that the field of such a body is regarded as the field of 2 horizontal cross hairs between poles or the field of a cylinder. In the second case, where 2b is large, the difference between the 2 figures will take on the appearance of a thin horizontal plate, the field of which is expressed by formula (4.9), on the condition that the factor Δh be added to the right side of the equation .

With an increase in h there is a change in the relationship between h and the vertical dimensions of the body and the concept that the body is "infinite" in its distribution by depth no longer holds. The general formula Z, for the case of a body with rectangular section, takes on the appearance

$$Z = 2I\left[\operatorname{arc\,tg}\frac{x+b}{h} - \operatorname{arc\,tg}\frac{x-b}{h} - \operatorname{arc\,tg}\frac{x+b}{h+d} + \operatorname{arc\,tg}\frac{x-b}{h+d}\right], \qquad (4,10)$$

in which d represents the cross-section of the body, along the vertical.

Analytical investigation of equation (4.10) does not result in the establishment of relationships capable of being expressed by simple formulas. If the values of d and of 2b are of the same order and the value of h significantly exceeds the linear dimensions of the cross-section of the body, the curve Z, corresponding with expression (4.10), is virtually indistinguishable at high altitude from the curve above a cylinder.

Figures 7 and 8 show in the form of curves the change in Z_{max} with altitude above a horizontal body, the quadratic section of which is (2b)(d), the section being calculated on equation (4.10). The dimensions along the vertical d = 1, the thickness 2b, and the height h, are expressible in unit d.

Figure 7 illustrates the change in Z_{max} between 0.1 and 1d, while Figure 8 illustrates it between 1 and 5d. The first drawing presents an idea as to the change Z_{max} during flights at altitudes by comparison with which the distribution of magnetized bodies in depth is considerable. The second drawing illustrates the change Z_{max} when the relationship of the magnitudes in question is the very opposite. In other words the former graphs are applicable in cases when the bodies are large in size relative to flight altitude while the second is applicable to small objects. Thus we see emphasized quite graphically the marked effect of flight altitude on the magnitude of the maximum Z to a greater degree, the smaller the dimensions of the bodies relative to altitude. Curves b:h = 0.1 and b:h = 1 in Figure 8 are very similar to the curve for diminution of Z_{max} over a cylinder.

Investigation of the expressions for the Z field over inclined bodies and bodies with oblique magnetization also fails to reveal relationships that may be expressed by simple formulas.

Figure 9 shows the Z field of an inclined stratum in vertical section. The vertical component Z is shown in the form of lines of equal value, the distribution of which illustrates the diminution of the field with height, while the scale of height is in units corresponding to the cross-sectional dimensions of the body.

Examination of the diagram gives rise to the question, important in practice, as to the displacement of Z_{max} along the x axis in proportion to the increase in altitude. At low altitudes the displacement of the maximum is most insignificant, but the angular displacement is in any case only a small fraction of the angle of decline of the stratum. As altitude increases, angular displacement rises somewhat, approximating 1/3 of the angle of decline in the upper portion of the drawing.

Let us examine the question analytically in terms of an obliquely magnetized cylinder, in which, as a result of the coming together of the polar lines, the displacement of the Z maxima along the x axis at various altitudes should be most clearly expressed.

The equation for Z for an obliquely magnetized horizontal circular cylinder is as follows

$$Z = 2M\frac{(h^2 - x^2)\cos\beta - 2hx\sin\beta}{(h^2 + x^2)^2}, \qquad (4,11)$$

in which β is the angle of deviation of the I vector from the vertical.

Compiling an equation for finding the abscissa of Z_{max} in the form of $\frac{\partial Z'}{\partial x}=0$, we obtain

$$x^3+3hx^2\operatorname{tg}\beta-3h^2x-h^3\operatorname{tg}\beta=0. \qquad (4.12)$$

In this equation x has 3 values. Depending upon the shape of the curve, one value, x_1, corresponds to Z_{max}, and 2 values, x_2 and x_3, correspond to 2 minimums, Z. The angle β exceeds 30° only in the southernmost portions of the USSR and is below that figure over most of its territory. Consequently the value of x_1 will be small relative to h, x_2 and x_3, while neither of the 2 latter values will equal infinity.

In finding the approximated value $x = x_1$, we write the value of x_1 into equation (4.12) and divide it, member by member, by h^3. Ignoring the second and third powers of the simple fraction $\frac{x_1}{h}$, we obtain

$$3x_1+h\operatorname{tg}\beta=0;\quad -\frac{x_1}{h}=\frac{1}{3}\operatorname{tg}\beta. \qquad (4.13)$$

Employing ϕ to designate the angular displacement of the Z_{max} point, we obtain:

$$\operatorname{tg}\varphi=\frac{x_1}{h}=-\frac{1}{3}\operatorname{tg}\beta;\quad \varphi\approx\frac{1}{3}\beta.$$

Figure 10 shows the values for Z at various levels, h_1 and h_2, over an obliquely magnetized cylinder. The displacement observed, Z_{max}, confirms the correctness of the approximate solution found. This conclusion is also confirmed by Figure 9. At an altitude which is high relative to the linear dimensions of the cross-section of the body, its field approximates the field of a cylinder of circular section. As a result we witness the gradual approximation of the angular deviation, Z_{max}, to 1/3 the angle of declination, with which the direction of the vector for intensity of magnetization coincides.

The deviation proceeds in the direction opposite to that of the dip. Later we shall show that when an inclined stratum is "infinite" in depth the deviation proceeds in the same direction as dip.

The theoretical examples we have examined provide a general idea of the changes in intensity of anomalous magnetic fields of geological bodies with variation in altitude.

The magnetic fields of geological bodies of various shapes and dimensions decline in proportion to distance from the earth's surface the more rapidly, the smaller are the dimensions of the body. Therefore the relationship among anomalies created by various bodies change with change in the altitude from which the survey is taken. Cases in which anomalies which are intensive at low levels of measurement rapidly diminish and become too slight to be recorded with increase in altitude, while adjacent weak anomalies related to large shapes are still noticeable at high altitudes, are possible, and have actually been found.

Figure 11 depicts the Z curve at 2 altitudes, about 100 and 400 m respectively above the earth's surface, over a body of iron ore of contact origin. At the lower altitude a sharply defined magnetic anomaly is seen, caused by an ore body and a skarn zone and a slightly elevated field above a massif of syenite. At an altitude of about 400 m the anomaly related to the ore body is practically unnoticeable and all that remains is the field above the syenites, while it has varied so little in intensity that at the given level of accuracy of measurement it is difficult to state that the vertical gradient of the Z field over the massif is of any quantitative significance.

Thus, examining the changes in the earth's magnetic field with variation in altitude, in terms of the sources of this field we find that the T_0 field of homogeneous magnetization will have a constant gradient of the order of 20 gammas per kilometer up to very high altitudes. Apparently the gradient of continental anomalies will be considerably lower than this. However the gradients of anomalies studied in the course of geological prospecting will be both positive and negative in sign, while their numerical values may be very high, particularly at the earth's surface.

5. Calculation of Field Intensity at a Given Altitude by Means of the Known Field Distribution at a Lower Plane

In the practice of magnetic prospecting cases are encountered in which the calculation of the magnetic field intensity for an altitude other than that for which it is known may prove very useful in the geological clarification of magnetic anomalies.

As it applies to the field above bodies of large area, and therefore in the form of a 2-dimensional problem, this question has been given detailed treatment in the works of B. A. Andreyev (1947, 1949, 1950, 1952, and 1954). These works present nomographic methods for finding Z and ΔT at a higher altitude by means of data for the field distribution at a lower altitude for bodies of large (theoretically of infinite) area, and for bodies of indefinite area, and also present a simple theoretical justification for the construction of nomographs.

As in the case of calculation of the H field in accordance with a given distribution of the Z field, we assume that the Z field given at a certain surface is produced by an imaginary superficial magnetic density, numerically equal, at each individual unit of space to $\frac{Z}{2\pi}$.

Let us first examine the 2-dimensional problem.

In order to calculate the field at point P let us employ the familiar formula expressing the value of Z over a vertical stratum small in size, 2b:

$$Z = 2\sigma 2b \frac{h}{h^2 + x^2}.$$

As applied to the given case, $\sigma = \frac{Z_i}{2\pi}$, $2b = dx$. Starting our coordinates at P and introducing the designation dZ to indicate that the field is being determined from the element dx, we obtain:

$$dZ(P) = \frac{Zh}{\pi (h^2 + x^2)} dx. \qquad (5,1)$$

The total value of Z(P) will be the integral of equation (5.1) within the range of minus to plus infinity. At any given limiting value, Δx, the field intensity $\Delta Z(P)$ will be

$$\Delta Z(P) = \frac{1}{\pi} \int_{x_m}^{x_{m+1}} Z \frac{h}{h^2 + x^2} dx =$$

$$= \frac{Z_i}{\pi} \left(\operatorname{arc\,tg} \frac{x_{m+1}}{h} - \operatorname{arc\,tg} \frac{x_m}{h} \right), \qquad (5,2)$$

in which Z_i is the mean value of Z in segment Δx in the interval from x_m to x_{m+1}. Let us divide the x axis into segments so that the difference in the arc tangents, given in parentheses, will be constant at any value of x_m. Let us assume, for example

$$\frac{1}{\pi} \left(\operatorname{arc\,tg} \frac{x_{m+1}}{h} - \operatorname{arc\,tg} \frac{x_m}{h} \right) = 0{,}05.$$

Then

$$Z(P) = 0{,}05 \Sigma Z_i;$$

In order to plot the nomogram, we derive

$$\operatorname{arc\,tg} \frac{x_{m+1}}{h} - \operatorname{arc\,tg} \frac{x_m}{h} = 0{,}157,$$

from which it follows that at a given value for the constant, the difference between the arc tangents is 9°. Consequently to plot the nomogram it is necessary to drop a perpendicular from point P, where the coordinates meet, and in addition to draw rays to left and right at 9° intervals to reach a horizontal (Figure 12).

The nomogram is drawn on tracing cloth or paper. It is used as follows. The Z curve is drawn along a line perpendicular to the axis of the anomaly. The density of the points of measurement should be sufficient for satisfactory interpolation of the field values in the intervals between points. If the measurements did not extend into the normal field beyond, the values lacking are determined by graphic extrapolation. The method recommended may not be regarded as less accurate than that of finding the residual integral on the assumption that the field fades in definite ratio, as the fading ratio is usually unknown to us.

The points for which the Z values are to be calculated are entered on the same graph. In applying these points we observe the scale on which the topographic profile has been drawn.

To find Z for a given point P, we connect the meeting point of the rays to point P. The central ray is vertical. The length of the rays should be such as to intersect the topographic profile set forth on the drawing. Then we calculate the Z_i sum, where Z_i is the mean value of Z for the given line in the interval between each 2 adjacent rays. The Z value sought at point P will be

$$Z(P) = 0{,}05 \Sigma Z_i. \qquad (5,3)$$

The Z value at other points is arrived at in the same manner.

If it should prove that the magnetic field varies very sharply in the interval between rays, so that it becomes difficult or impossible to determine the average value, one of the following methods must be used. Either (a) with no change in the nomogram, Z is calculated for intermediate altitudes, and the desired altitude is approached step by step, or (b) a different nomogram is employed, with smaller intervals, that is, 4.5°. In this case the formula for calculating

Z will be:

$$Z = 0{,}025\ \Sigma Z_i.$$

Let us examine a specific case of calculation of Z at the new level (Figure 23). It is best to plot the graph for a constant height, for example, 10 mm. Its value in meters is determined by the scale used in the given graph. For more accurate derivation of average values at points distant from the central point it is desirable to divide the broad intervals into segments. In our drawing the eighth interval (between 63 and 72°) is divided in 2, the ninth into 3 parts at 3° intervals, and the tenth into 5 at 1.8° intervals, only two-fifths being shown on the drawing. Let us write in the average Z_i values in millimeters in the intervals to the right of the central line: $22+22{,}5+22{,}5+22+21+17{,}5+12+\frac{1}{2}(6{,}5+3{,}5)+\frac{1}{3}(-1-4-6)+\frac{1}{5}(-4{,}5-3)=139.$ On the left side we get $22+21+20+19+17+16+15+\frac{1}{2}(17+17)+\frac{1}{3}(11+4+2{,}5)+\frac{1}{5}(3+0{,}5)=154.$ From this we derive $Z(P)=0{,}05(139+154)=14{,}6$ мм.

In a case in which the Z field or ΔT given for the initial surface plane has no clearly defined axis and the hypothesis of infinite area is permissible, the calculation of the Z field or of ΔT at the new, higher level proceeds as follows.

Let us assume the Z field distribution at some plane surface. In any element ds the given value of Z may be examined as the result of an imaginary magnetic mass σ with a density of $\frac{Z}{2\pi}$. In that case the dZ field, at point P, and altitude h, will be (Formula 100 in Logachev, 1951):

$$dZ = \frac{\sigma ds h}{r^3} = \frac{Zhds}{2\pi r^3} = \frac{Zhdr d\theta}{2\pi r^2}. \qquad (5,4)$$

Here r is the distance from the P point to the ds element. θ is the angle formed by the projection of r to the plane in which

P lies, and by a fixed direction $ds = rdrd\theta$.

Let us break up the entire plane containing the given Z values into areas of equal effect. Within these areas we will take Z to be a constant equal to the average value of Z_i. The field $\Delta Z(P)$ of such a space will be expressed by the formula

$$\Delta Z(P) = \frac{Z_i}{2\pi}\int_{r_m}^{r_{m+1}} \frac{h}{r^2}\,dr \int_{\theta_n}^{\theta_{n+1}} d\theta =$$

$$= \frac{Z_i}{2\pi}\left(\frac{h}{r_m} - \frac{h}{r_{m+1}}\right)(\theta_{m+1} - \theta_m).$$

Assuming $\theta_{m+1} - \theta_m = 36^\circ = 0{,}628,$

$$\frac{h}{r_n} - \frac{h}{r_{n+1}} = 0{,}1, \qquad (5{,}5)$$

in which case

$$Z(P) = 0{,}01\,\Sigma Z_i. \qquad (5{,}6)$$

Let us plot a nomogram to permit Z(P) to be found. From the center point O we draw rays at 36° intervals and then circles, the radii of which, x_i, are obtained from equation (5.5):

$$\frac{h}{\sqrt{h^2 + x_m^2}} - \frac{h}{\sqrt{h^2 + x_{m+1}^2}} = 0{,}1.$$

Taking h = 1, we find

$$\frac{1}{\sqrt{1 + x_m^2}} - \frac{1}{\sqrt{1 + x_{m+1}^2}} = 0{,}1,$$

from which we derive the following values for x_i 0; 0,48; 0,75; 1,02; 1,33; 1,73; 2,28; 3,17; 4,91; 9,8; ∞. If we take the height h in the given scale to be, for example, 20 mm, the successive radii will be 0; 9,6; 15;20; 26,6 мм. See Figure 14.

In deriving the field at some point P and altitude h, the nomogram is laid atop the chart of the magnetic field in such a manner that its center corresponds with point P. Determination is then made of the mean value Z_i within each space, formed by rays and circles, subsequent to which we calculate the sum Z_i. The value desired is calculated on equation (5.6).

Let us examine the calculation of Z in terms of a specific example (Figure 15). Let us assume that we are required to calculate the field at height h, which is 10 mm on the scale presented by the chart. Now let us plot a graph for h = 10 mm. Let us place the center of the grid at point P and calculate the total of average Z_i values for each space. Within the circle for the first radius the Z_i values will be (counting clockwise from the vertical) $50+6\cdot45+3\cdot50=470$. In the second ring, they will be $50+5\cdot40+50+$ $+3\cdot60=480$; In the third $2\cdot50+2\cdot35+2\cdot40+50+3\cdot60=480$; In the fourth $2\cdot50+2\cdot30+2\cdot40+50+3\cdot70=500$; In the fifth $60+40+2\cdot20+2\cdot40+2\cdot65+2\cdot90=530$; In the sixth $50+30\cdot$ $+2\cdot15+2\cdot40+2\cdot65+2\cdot80=480$; In the seventh $40+20+0+10+2\cdot40$ $+60+3\cdot50=360$; In the eighth $2\cdot10-20+10+20+40+50$ $+3\cdot20=180$; In the ninth $-10-20-10+10=-30$.

On the basis of equation (5.6) we find that $Z(P) = 0.01 \cdot 3450 = 34.5$. The results are obtained in the same units in which Z is given in the original drawing.

6. Calculation of Field Intensity at Points below the Plane in Which Field Distribution is Known

Determination of an anomalous magnetic field at various levels below the plane in which field distribution is known increases the possibilities for practical utilization of the data of magnetic survey for the study of geological structure, as is confirmed by well-known works in this field (Andreyev, 1947, 1949, 1952, and 1954, and Veynberg, 1944). The possibilities of practical employment of the field distribution in the vertical section above and below the given level are apparently subject to considerable expansion. In particular we have in mind the plotting of a vector diagram of the T_a field (the "magnetic spectrum") [illegible] illustration of the vertical differentiation of rocks by magnetic intensity. Derivation of the full T_a vector presents no difficulty, as with a given distribution of the Z_a or ΔT field at a given altitude it becomes possible to calculate the H_a field and thereby to derive the total vector on the basis of the 2 components.

In order to calculate the Z field below the given level, where the problem is 2-dimensional, we make use of the solution proposed by B. A. Andreyev in 1954.

Let us take as given the values of $Z(x,0)$ along a line x, the direction of which is perpendicular to the long axis of the magnetized body. Let us assume the height of the axis of the abscissa to be $z = 0$. The problem consists of finding the values $Z(x', h)$ at point x', located at depth h in the identical vertical section.

The first approximation $Z_0(x',h)$ is found on the basis of theorems having to do with the mean value of the potential function for the 2-dimensional problem. The value of the function at the center of the circle is the arithmetical mean of the values of the functions on the circle itself.

For purposes of an approximated solution we employ the values of the functions only at certain points along the circle, to wit, those at the points of an inscribed regular hexagon or square.

Let us assume that the values of the Z function are known at 4 points located at the apices of a square $h\sqrt{2}$ on a side (Figure 16). Then the value of the Z function at the center of the square will be determined by the theorem for mean value:

$$Z(x', 0) \approx \frac{1}{4}[Z(x'+h, 0) + Z(x'-h, 0) + Z(x', h) + Z(x', -h)]. \qquad (6,1)$$

However, if the values of Z are known at all points other than (x',h), the value at that point is determined from equation (6.1):

$$Z(x', h) \approx 4Z(x', 0) - [Z(x' + h, 0) + Z(x' - h, 0) + Z(x', -h)]. \qquad (6,2)$$

In the case under examination, the values of Z at point $(x', 0)$, $(x'+h, 0)$ and $(x'-h, 0)$ are the given values at the initial level $z = 0$, while the value of Z at point $(x',-h)$, that is, at h elevation above the initial level may readily be calculated by the method set forth above. Thus on the right side of equation (6.2) all 4 members may be taken as known, so that the value of Z is found at point (x',h).

The process is assisted by the use of a template in the form of a sheet of paper with openings cut in such a manner as to reveal only the corners and center of the square, that is, the values of Z at the points required.

Thus we find the value of Z at depth h along the entire x line at intervals such as to permit the plotting of an uninterrupted curve.

In order to find the second approximation we regard the values $Z(x,h)$ as given. On these values we calculate $Z(x,0)$, which are the figures truly given. Let us assume that the value of Z calculated at point $(x',0)$ has proved equal to $Z'(x',0)$ and that the true value is $Z(x',0)$. The difference $\Delta Z_1 = Z(x',0) - Z'(x',0)$ is the first correction to be made in the value of $Z(x',h)$. Corrections of this kind are found for a number of points, subsequent to which we draw the corrected curve $Z_1(x,h)$.

Further, the same method may be employed to find the second correction ΔZ_2, by the magnitude of which we correct curve $Z_1(x,h)$, as a result of which we obtain a new and more accurate value for $Z_2(x,h)$. Experience has shown that in calculating the Z field at a depth h, consituting a small fraction of the depth at which the top of the given body is located, it is adequate to make but a single correction. In this case, when the length of the anomaly is not clearly defined at the initial level and it is not possible to apply the theory for a field in bodies of infinite length, the problem of deriving the field at points below the given surface is resolved in a manner analogous to the foregoing on the basis of theorems covering the average value of the potential function at the center of a sphere.

In view of the unconscionable amount of work involved in resolving the problem if we employ a large number of points on the surface of a sphere, we shall limit ourselves to the corners of a regular hexagon inscribed in a sphere, 3 corners of which are in the plane of the known field, and 2 of which are disposed symmetrically, one above and one below it. Let the Z (or ΔT) field in the plane of observation be: in the center of sphere, Z_1; at the corners of the hexagon, Z_2, Z_3, and Z_4. The Z_5 field may be calculated in the manner set forth above for the case of a 3-dimensional problem. In that case the Z field at the point corresponding to the lowest corner of the hexagon will be

$$Z = 5Z_1 - (Z_2 + Z_3 + Z_4 + Z_5).$$

After determination of the Z field at an adequate number of points in the plane below the given plane, the correction may be found in the same manner as indicated for the 2-dimensional problem as follows. The field in the lower plane is regarded as that given, while the value of Z is calculated for that field on the basis of points in the initial plane. The differences arrived at between the true and calculated values of Z are employed as the first corrections to the values calculated at points for the lower plane.

CHAPTER II. THE UTILIZATION OF ANOMALOUS MAGNETIC FIELDS IN GEOLOGICAL PROSPECTING

7. Determination of the Course and Countours of Geological Structure by the Data of Aerial Magnetic Surveys

The results of measurements of the magnetic field presented in topographical fashion in the form of curves for a field undergoing continuous change along each route or in the form of isolines on a map reveal in graphic form the course and approximate contours of both large and small geological structures, depending upon the scale of the survey.

We know that world charts of the geomagnetic field compiled on a fairly small number of absolute magnetic measurements, have been employed by various authors to explain the fundamental structural elements of the earth's crust. Thus N. N. Trubyachinskiy in 1934 determined the connection between the direction of isogonics (lines of equal inclination) and the course of geosynclines. In order to clarify the structure of the pre-Cambrian foundation of the east European platform, A. D. Arkhangel'skiy made successful use in 1941 of the map of magnetic anomalies in the European portion of the USSR, compiled on the basis of absolute magnetic measurements set forth approximately on a 20x20 km graph.

The practical significance of large scale survey in establishing the course and contours of geological structures is generally known and is confirmed by all past experience in magnetic survey.

Magnetic charts compiled on the data of aerial magnetic survey constitute valuable data for the solution of the questions under examination, as they are always compiled for large areas and equally spaced routes and for uninterrupted measurement of the field for each route. Also of positive significance is the fact that in order to determine and follow a structure of given scale, aerial surveying should be performed at a given distance from the earth's surface to exclude the effects of small shapes of highly magnetized rocks which excessively complicate the magnetic fields of the large structures being studied.

Determination of the course of such rocks, distinguished from intrusive rocks by their magnetic properties, is not particularly difficult if the dimension of the body along the strike is several times as large as the distance between survey routes and the direction of the latter forms a significant angle, approximating a right angle with the strike axis. This is a direct conclusion from the data in Figure 17 illustrating a field Z_a over the area of distribution of highly metamorphosed ancient rocks, containing rocks of high magnetic intensity. The methods of determining the contours of magnetized bodies (in this case their visible thickness) require a mathematical foundation.

Let us examine the simplest case, in which the magnetized body takes the form of a vertical stratum the thickness of which is 2b. We will consider the distribution of the body in depth to be large relative to the depth at which it is located, while our concept of depth will include flight altitude.

Employing the familiar formula for a field in a case of direct magnetization, which is

$$Z = 2I\left[\operatorname{arc\,tg}\frac{x+b}{h} - \operatorname{arc\,tg}\frac{x-b}{h}\right],$$

let us find the first derivative of the function of Z in accordance with x. The curve $\frac{\partial Z}{\partial x}$ will have one maximum and one minimum, the abscissas of which may be found if we take $\frac{\partial^2 Z}{\partial x^2} = 0$. Solving the equation, we find its real roots:

$$x^2 = \frac{1}{3}\left[b^2 - h^2 + 2\sqrt{b^4 + h^4 + b^2h^2}\right].$$

Assuming that $h \approx b$, we derive the approximated value of the abscissas of the extreme points on the curve $\frac{\partial Z}{\partial x}$: $x \approx \pm 1{,}1b$. If $b > h$, the approximated value of the abscissas for this point will be $x \approx \pm b$. However, if $h > b$, then we will obtain, accordingly $x^2 \approx \frac{2}{3} b^2 + \frac{1}{3} h^2$. From this it follows that the lateral boundaries of bodies of the desired form are determined by the location of the extreme values, $\frac{\partial Z}{\partial x}$, which, as we know, correspond to the location of the points representing the breaks in the curves. If the distance between the abscissas for the points constituting the break are significantly greater than the depth of the stratum (including the flight altitude), the boundaries of the body may be determined to an accuracy close to that of the graphic method of finding the points representing the break in the given curve. However, if the thickness of the body is less than the flight altitude, the boundaries are determined only approximately.

The conclusions drawn for the special case of the symmetrical curves Z may be employed to delineate the contours of the magnetized bodies and for assymetrical curves as well. This may be proved without recourse to the mathematical analysis of the complex expressions determining the Z field in oblique magnetization.

If we are given the Z field over an inclined stratum the thickness of which is 2b, the expression $\overline{\frac{\partial Z}{\partial x}\Delta x}$ may be regarded as the vertical component over 2 strata, the distance between which is 2b, formed by the real side surfaces of the stratum and the surfaces parallel thereto, displaced to a distance of Δx, while the intensity of their magnetization has exactly the reverse signs (Figure 18). Ignoring the slight shift along the x axis of the largest values for the gradient relative to the upper edge of imaginary thin strata, it is possible to obtain an approximated idea of the contours of magnetized bodies by employing the maximum and minimum of the function $\frac{\partial Z}{\partial x}$, or, what amounts to the same thing, the break points on curve Z. This is fully applicable to assymetrical curves as well. It is obvious that this method is no obstacle to very gradual diminution when the shift in the break points is considerable. However the very effort to employ this method is unsuccessful in view of the practical impossibility of finding the break points on the drop-off side of the body.

The possibility of employing magnetic measurements to determine the borders of the upper edge of a body dropping away very gradually is entirely dependent upon the expressiveness of the Z (or ΔT) curves above the portion where the upper edge terminates and the side surface of the inclined body begins.

The limited distribution of inclined bodies in depth naturally tends to affect some shift in the extreme values of $\frac{\partial Z}{\partial x}$ relative to the projection of the boundaries of the upper edge to the plane of observation. However this displacement cannot be very large. Let us assume that the body shows some slight distribution in depth. In this case imaginary bodies cut into the side boundaries, the field of which is expressed by the formula $\frac{\partial Z}{\partial x} \Delta x$, may be regarded as cylinders. In this case the angular displacement of the Z maximum relative to the axial line attains 1/3 of the angle of slope of the vector for intensity of magnetization, which may be ignored in approximated determination of the boundaries of the body.

For purposes of more exact determination of the boundaries of the magnetized rocks it is possible to go over to the use of higher derivatives. This question will be examined in conjunction with problems of calculation of depth.

Returning to Figure 17, on which the course of the magnetized rocks is distinctly visible, we are compelled to conclude that determination of the thickness of the magnetized bodies is impossible in the given instance due to the small width of the anomaly and the inadequate accuracy of the measurements. The survey was made with a Z aeromagnetometer with an error of the order of 100 gammas. So large an error rules out the possibility of reliable determination of the points of inflexion on the narrow peaks of the Z field.

Let us examine another example, based on use of the T-aeromagnetometer. Figure 19 shows the ΔT field for a relatively small area of Western Siberia. The course of the structure, determined by the direction of the axes of the magnetic anomalies, leaves no question for doubt. As far as the contours of the rocks constituting the magnetic anomalies are concerned, they are determined with sufficient accuracy by means of points of inflexion in the ΔT curves, as shown in Figure 19. In following the axes of the anomalies and the contours of the magnetized bodies it is necessary to take into account the possible displacement of the anomalies due to errors in orientation, so that it is not necessary to adhere too strictly to the abscissas for the points of inflexion on each trip.

The question as to determination of the contours of magnetized bodies is resolved easily for cases of simple anomalies created by isolated magnetized bodies or formations including magnetic and nonmagnetic rocks succeeding each other at intervals that may be deemed small in terms of flight altitude. In examining complex anomalies which in vertical section present a number of relative maxima and minima for the Z (or ΔT) curve, repeated on adjacent trip routes, the differentiation of rocks by intensity of magnetization (and consequently by composition) becomes more complex.

As the width of the anomalies increases with increase in the altitude of the plane of measurement, cases may arise in which 2 or a number of bodies actually at some distance from each other form a common anomaly with unnoticeable or faintly delineated fluctuations in the field in the central portion of the positive values of Z (or ΔT), as happens for instance in the situation shown in Figure 20. Differentiation of such anomalies is facilitated by plotting the curve for the $\frac{\partial Z}{\partial x}$ c gradient, with subsequent employment of the abscissas of the extreme values of the curve to arrive at approximated location of the boundaries of the magnetized bodies.

The inaccuracy of the determination of the boundaries in the given instance is due to displacement of the extreme values possibly as a result of the body being in an inclined position, with oblique magnetization, and also due to the superimposition of the field of each body upon that of others. However these displacements cannot be so large that these errors compel the abandonment of the method. In case of doubt it is always possible to check the correctness of the profile arrived at, after the depth of the stratum has been determined, by calculating the field for the profile determined and checking this against the observed data.

Figure 21 illustrates one of the curves presented in Figure 20, and the curve for $\frac{\partial (\Delta T)}{\partial x}$ is plotted. The curve of the gradient determines the boundaries of the magnetized bodies more exactly, although they may be found without plotting the gradient curve by direct employment of the ΔT curve as shown in Figure 20.

The same drawing clearly reveals anomalies, small in area but significant in intensity, which in the given example happen to be formed by trap rock. The small scale on which the given survey was taken renders it impossible to determine the contours of the individual small bodies but the scale is adequate for ready determination of their zone of distribution.

It is unnecessary to extent further our selection of examples from aerial magnetic survey as performed in practice to illustrate the clear reflection of the course and contours of magnetized rocks. Let us now adduce examples of a different type, covering conditions in which contours of nonmagnetic or weakly magnetized rocks are identifiable as a result of changes in the magnetic field over the surrounding rocks. Figure 22 shows the Z field over a portion of Western Siberia. Here small anomalies over enriched magnetite rocks in the midst of trap rock clearly mark off the borders of an emergence of ancient rocks, over which we note a uniform and slightly elevated field. Figure 23 illustrates the geological structure of this area. Figure 24 shows the identification of a granite intrusion by changes in the Z field in the contact zone and Figure 25 identification of granites by the elevated field above the surrounding rocks.

The examples adduced illustrate well known conclusions from the practice of aerial magnetic survey, confirming the fact that it is possible to determine the extent and contours of geological structures. Further elaboration of the data of aerial magnetic survey simultaneous with calculation of the depth of the top of the magnetized bodies makes it possible for the contours of bodies established to a first approximation to be rendered more precise.

8. Determination of Depth of Occurrence of Magnetized Bodies

The problem of determining the depth of occurrence of the tops of magnetized bodies is of fundamental importance in magnetic survey and most particularly in aerial survey. Correct solution of the problem of the depth of the upper surface provides very valuable data for the general geological interpretation of the findings of aerial magnetic surveys and opens the way to the determination of such other characteristics of the occurence as thickness and angle of dip, and in some cases for approximate determination of the depth of the lower edge of the body and, finally, the average intensity of magnetization of the rocks. It is natural that the major efforts of many researchers have been directed to the solution of this specific problem. The results of this research have been the advancement of a number of specific methods for the solution of the problem, ranging from simple graphic methods to methods requiring complex mathematical calculations.

None of the known methods of solution is universal and applicable to any and all specific anomalies. Successful utilization of the methods developed to determine depth demands careful preliminary examination of concrete geophysical data and allowance for the geological environment so as to determine the most satisfactory solution under the given conditions. Mechanical adoption of any single method to all the anomalies found by surveying would lead to crude errors in the geological conclusions arrived at. This is particularly true of simple methods of calculation not requiring any considerable expenditure of labor, which as a result have come into widest use. It does not follow from this that simple methods should not find application in practice. On the contrary it is essential under all circumstances to seek to reduce the labor outlay on calculation, and complex methods should be avoided where a problem that has arisen may be resolved more simply. Here we emphasize the necessity for compulsory investigation of the applicability of the selected method of resolving the problem and the choice of that method which is capable of providing the most precise solution of the problem regardless of the complexity or simplicity of the method.

Calculation of the depth of occurrence by means of the data of aerial magnetic survey differs in certain respects from calculations based on the materials of survey made at ground level.

The absolute error in the calculation of the depth of occurrence of the objects of investigation increases in accordance with the increase in flight altitude due to the reduction in the absolute intensity of the anomaly and consequently the increase in the relative error of the measurement.

The calculated depth is the sum of the flight altitude and the real depth of occurrence, while the practical depth is that measured relative to the earth's surface. We obtain the latter by subtracting the flight altitude, but the accuracy of the latter will be the less satisfactory, the lower the actual depth of occurrence. Let us assume for example that at an altitude of 300 m the depth of occurrence is found to be 300±30 m. Relative to the plane of observation, determination of depth to an accuracy of ±10% may be taken as satisfactory. However, when the depth of occurrence is thought of relative to the earth's surface, one obtains a result the practical value of which is highly dubious. However, if from the same flight altitude the depth of occurrence be found to be, say, 1,000±100 m, with the same error of ±10%, then recalculation to find depth relative to the earth's surface will yield 700±100 m. Consequently satisfactory results are capable of being obtained relative to large objects at considerable depth. However, as concerns small objects found at little depth relative to flight altitude, measurements at the earth's surface are required to increase the accuracy of the solution of the problem.

The simplest methods of calculating the depth of occurrence of the upper surface of magnetized bodies are graphic. They include the long familiar method consisting of finding the points (or limited areas) at which intersection occurs between the direction of the total T_a vectors, these loci being taken to coincide with the top edge of the magnetized body. The applicability of this method is limited to strata of limted thickness relative to depth of occurrence but covering a considerable range of depth. The method is uniformly applicable to vertical and inclined strata, with direct and oblique magnetization. Depending upon the real thickness of the body, the depth of occurrence found in this way is always somewhat greater than the depth of the upper edge, in accordance with the location of imaginary "polar lines" within the body. Whether or not this method is applicable is revealed in the course of its utilization. In order to apply this method to the results of aerial magnetic survey it is necessary first to calculate H_a for the known ΔT field, taking the latter to be Z_a in indirect magnetization.

A method based on the proposition that the depth of the top of the occurrence is equal to half the distance between points on the Z curve, when $Z = 0.5Z_{max}$, has found wide dissemination.

This proposition is entirely applicable only in cases in which a symmetrical Z curve is encountered in connection with a vertical stratum of considerable length, limited thickness (relative to depth), and considerable distribution in depth. Consequently the use of the method is proper only when the magnetized body is of a shape similar to that indicated. Under all other conditions the relationship thus examined is out of place.

Yu. N. Grachev has proposed a graphic method of resolving the problem, taking into account the horizontal dimensions of the body in a direction perpendicular to its course. Tangents are drawn to the Z (or ΔT) curve, as follows: one, parallel to the x axis and at the top of the curve, others to the points of inflection of the right and left arms of the curve, and, finally, tangents parallel to the x axis, and touching the right and left minima. From the 2 points of intersection of the sloping tangents and the upper horizontal tangents, perpendiculars are dropped to the lower horizontal tangents. Then, in accordance with the signs of the abscissas for the points of intersection of the tangents shown in Figure 26, the depth is calculated on the empirical formula

$$h=\frac{1}{2}\left[\frac{1}{2}(x_1-x_2)+\frac{1}{2}(x_3-x_4)\right].$$

Application of this formula in approximated evaluation of depth are limited to cases of vertical and near-vertical strata of large variation in depth. The error increases very sharply with increase in angle of dip or reduction in the size of the body with depth. This method has come into wide use by aerial magnetic survey teams. No fault can be found with it when it is used critically for preliminary general determination of the depth of occurrence of magnetized bodies. However, aerial magnetic data of high accuracy permits more stringent analysis than the foregoing and consequently more accurate calculation of depths and sometimes of other characteristics of the occurrence.

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In recent years a number of writers have proposed graphic methods consisting of comparison of the observed Z or H curves with the theoretical curves calculated for groups of bodies of large area, with changing relationships among the linear dimensions of each section. All the methods proposed up to this moment involve the utilization of symmetrical curves only. These methods are set forth briefly in a special section hereunder.

The graphic method of determining depth of occurrence by plotting the magnetic spectrum, which would appear to offer good prospects, has not been worked out to the state at which it can be recommended for widespread use.

In the majority of works of most investigators one encounters examination of the possibility of analytic calculation of depth. In addition to the methods, treated elsewhere, of calculating the depth of occurrence of isolated bodies of simple forms by means of analytical equations for a field corresponding to the hypothetical shape of the body, various authors have suggested methods for calculating the depth of occurrence of bodies of more complex forms by plotting the integral functions of fields Z and H. Among these is the method advanced by A. P. Kazanskiy, described in detail in the literature (1938_1, 1938_2, 1950), and proposed for the purpose of calculating the coordinates of the center of gravity of the cross-section of a greatly elongated or triaxial body. This method is not employed in practical aerial magnetic survey because the depth of occurrence of the center of gravity of the section is only rarely of practical interest. In addition the applicability of methods of integration is highly limited by the fact that they have been developed for the special case of vertical magnetization and always demand employment of data on the profile of the field, the length of which exceeds the depth of occurrence many fold.

A significant modification proposed by G. A. Gamburtsev (1938, 1940) for the purpose of calculating the depth of the upper edge of the deposit in terms of the field of an imaginary body constituting a shearing of the upper surface (the "difference" between the real body and the same body subjected to slight displacement along its vertical axis) has also failed to contribute to the introduction of methods employing integration, as the limits to the application of these methods, consisting in the requirement that a particular case of magnetization be employed and demanding that the profile be greatly extended, have not been eliminated.

B. A. Andreyev has proposed a method of calculating depth which is founded on study of the changes in a field determined beneath the given plane (cf. 1954, 1948, 1950). This method is worthy of special attention as it does not require prior determination of the shape of the body. However the criteria proposed by the author for determining the depth of the top of a body by changes in the field at the boundary between media of differing magnetic properties has proved inadequate. Consequently it is not now possible to recommend this method in its present form.

Later works by the same author, envisaging the finding of the "maximum distribution of the field" and noting the coincidence between the latter and the upper edge of the body, are applicable in limited instances where there are strata covering a wide depth interval, magnetized in the direction of dip.

T. N. Simonenko (Roze) has proposed a method of approximated calculation of the depth of occurrence by means of the ultimate value of a function in the form of

$$\overline{\lim x^2 Z_{x \to \infty} = 2\mu h,}$$

in which h is the depth of occurrence of the upper edge of a magnetized body of large extent, covering a large depth interval, while μ is the density of the magnetic mass at the upper portion of a section through the body.

Employing the familiar formula (cf. Logachev, 1951) for the case under examination, the following expression is valid

$$\int_{-\infty}^{\infty} Z dx = 2\pi\mu,$$

Employing this equation, the author of the method in question provides the following formula for his calculations:

$$h = \pi \frac{\lim x^2 Z_{x \to \infty}}{\int_{-\infty}^{\infty} Z dx}.$$

Study of this formula and of the experience acquired by its employment in the elaboration of data obtained by aerial magnetic survey confirms the possibility of obtaining sufficiently satisfactory results by way of a first approximation.

On the basis of study of the applicability of various methods of calculating the depth of occurrence by means of the Z (or Δ T) field, we may draw the conclusion that, in instances of simple anomalies, when the anomaly above a specific body is not complicated by the effects of the fields of other bodies, depth of occurrence may be determined by a variety of methods. However in the case of complex anomalies the problem often becomes insoluble.

From the theoretical considerations confirmed by experience gained by the use of various methods of calculating the depth of the top of an occurrence, it follows that where complex magnetic anomalies are concerned the best results are obtained not with integral functions but with higher derivatives. In the latter case the effect of the more distant magnetic masses declines with relatively greater rapidity, with the result that the magnetic field of magnetic masses close nearby, such as those which are attributable to the surface of the magnetized body, emerge in sharper relief. In connection therewith, we shall hereafter devote our main attention to methods based on the employment of the higher derivatives of the magnetic potential calculated on the measured values of the Z or the ΔT field, in addition to our consideration of simple methods of calculating the characteristics of occurrence for isolated bodies.

9. Calculation of the Characteristics of Occurrence of Magnetized Bodies of the Simplest Shapes by Means of the Analytic Expression for Field Intensity

If the intensity of a known magnetic field over a magnetized body is capable of expression by a mathematical formula, the parameters of which do not appear in explicit fashion, the possibility exists in principle of calculating all the parameters, as the known distribution of the field over a given surface makes it possible to work out the necessary number of equations. The practical possibility for the solution of the problem depends upon determination of the value of the field at points the use of which would yield simple and readily soluble equations.

Equations of this type have been found for bodies of the simplest forms (Logachev, 1951) and ready formulas have been compiled for calculating the characteristics of occurrence. These formulas envisage the employment of values for the field at points which may readily be plotted on the plan chart.

The difficulty involved in the employment of prepared formulas lies in the fact that their employment requires preliminary determination of appropriate models of the simplest forms, similar in form to the real body giving rise to the anomaly. It is by no means always possible to meet the condition satisfactorily, while the error in choice of model and of ready formulas corresponding thereto for purposes of calculation involve the possibility of wide error in determining the characteristics of the occurrence.

The methods of solving problems as to the depth of occurrence of bodies of simplest form have been set forth in the journals and textbook literature. Here we shall only present certain general considerations and supplements.

In the employment of ready formulas for calculating the characteristics of occurrence of magnetized bodies limited in extent, the first problem that arises is the permissibility of employing formulas derived for bodies of infinite extent. A relative approximation of the dimensions of bodies depends upon the depth of occurrence, as, in aerial surveys, the "depth of occurrence" increases, and it is thus necessary to use some other basis for scale in determining dimensions.

Let us find the expression for the Z field along a line x over a vertical stratum of limited thickness and covering a large depth interval, the dimension along the long axis being 2 l. This condition requires that in deriving the formula a substitution be made for the limit of integration along the long axis. Instead of the limits being from 0 to $1/2\pi$ it is necessary to employ the range from zero to $\operatorname{arctg}\frac{l}{\sqrt{h^2+x^2}} = \arcsin\frac{l}{\sqrt{h^2+x^2+l^2}}$.

As a result we have

$$Z = Z_\infty \frac{l}{\sqrt{h^2+x^2+l^2}},$$

in which Z_∞ is the value of Z when $l = \infty$, and h is the depth of occurrence of the upper edge.

With l unchanged, the multiplier declines as h and x increase, given Z ∞. Let us consider a deviation of 10% to be permissible. Let us find, subject to that condition, the criteria within which the concept of infinite extent is permissible.

At a point x = 0, that is, above the middle of the stratum $Z = Z_\infty \frac{l}{\sqrt{h^2 + l^2}}$, from which, assuming $\frac{l}{\sqrt{h^2 + l^2}} > 0,9$, we find $l > 2h$. In other words in order for the difference between Z and Z_∞ not to exceed 10% in the region of maximum values, the dimensions in the direction of the long axis must be 4 times as great as the depth of the occurrence.

If the course is infinite the isoline $Z = 1/2 Z_{max}$ passes at a distance of x = h. Let us assume this relationship to be maintained approximately for highly elongated bodies of finite course. In order for the Z field to differ from the Z_∞ field at points x = h by not more than 10%, the expression $l > 3h$ must be satisfied.

Let us plot the contours of the isoline $Z = 1/2 Z_{max}$. The longer axis of this contour is approximately 2 l and the smaller, 2 h. As a consequence it is necessary, in order for the inequality to be fulfilled, that the axial ratio of the contour under study exceed 3.

The ratio between the axes of an oval contour makes it possible to make use of the values of Z along a line x passing above the center of the occurrence, within the contour $Z = 1/2 Z_{max}$, with the assurance that any value of $Z > 1/2 Z_{max}$ differs from the corresponding value of Z_∞ by less than 10%.

If in the process of resolving the problem it becomes necessary to make use of smaller values for Z, it is essential to find the permissible ratio for the axes of the oval contour of the corresponding isoline. For example in using the isoline $Z = 0.2Z_{max}$, in which $x = 2h$, we find that $l > 4{,}5h$, that is, the axial ratio must exceed 4.5.

If the body is very thick, but the thickness does not exceed its depth of occurrence (allowing for flight altitude), the axial ratio thus determined increases slightly.

With bodies covering only a small interval in depth, the axial ratio declines, assuming the same permissible error.

Generalizing the conclusions arrived at for bodies of differing section, it may be taken as a general rule that, in order for formulas derived for bodies of infinite extent to be applied, it is necessary for the axial ratio of the oval contours of the isolines employed to be not less than 4 to 5-1. When this is the case, the centered profile is employed for the calculations. If the axial ratio is larger, one may employ several profiles, separated from the central by a distance not greater than the section which is ruled out in the extreme case of axial ratio. When the ratio is smaller, the use of formulas suited to infinite extent is only possible if corrections are made that are calculated for concrete conditions, or if formulas are used which are derived for equiaxial bodies.

The magnetic field Z of equiaxial bodies are characterized in plan view by concentric isolines for positive values surrounded by a weak negative field, vertical magnetization being assumed. Finding the center of such a body and its magnetic moment presents no difficulties, while calculation of the top of the body is possible only if supplementary data as to intensity of magnetization is at hand.

The literature offers nothing on calculating characteristics of occurrence in the case of oblique magnetization. In actual practice if equiaxial bodies are encountered they always have asymmetrical Z fields (and ΔT fields which are even more assymetrical). The theoretical Z (or ΔT) field occurring in oblique magnetization over a body of spherical shape is illustrated in Figure 27. Let us indicate here a method of finding the depth of the center in a case where the field is distributed assymetrically.

The expression for the Z field in oblique magnetization (or of the ΔT field in direct magnetization) over a body of spherical shape along a line passing through the epicenter of the occurrence, takes on the following appearance (Logachev, 1951):

$$Z = \frac{M}{(h^2+x^2)^{5/2}}[(2h^2 - x^2)\sin i + 3hx\cos i\cos A], \qquad (9,1)$$

in which h is the depth of the center, M is the magnetic moment of the body, A is the magnetic azimuth of the chosen trend of profile, and i is the angle of inclination of the T vector. The extreme values of Z are found from the equation $\frac{\partial Z}{\partial x} = 0$:

$$h^3\cos i\cos A - 4h^2x\sin i - 4hx^2\cos i\cos A + x^3\sin i = 0. \qquad (9,2)$$

Making use of the fact that the Z_{max} abscissa which we denote by x_m is small relative to the depth and abscissas of the 2 minima for Z, let us divide equation (9.2) by h^3, and discard the second and third powers of the x_m:h ratio. Thus we obtain the equation

$$h\cos i\cos A - 4x_m\sin i = 0,$$

from which we find

$$4\frac{x_m}{h} = \operatorname{ctg} i\cos A \qquad (9,3)$$

[illegible] $= 0$ in equation (9.1), we obtain an equation for points x_1 and x_2:

$$2h^3 - x_{1,2}^2 + 3hx_{1,2}\operatorname{ctg} i \cos A = 0. \qquad (9,4)$$

From equations (9.3) and (9.4) we obtain

$$x_{1,2}^2 - 12x_m x_{1,2} - 2h^2 = 0. \qquad (9,5)$$

As abscissas x_1, x_2, and x_m are plotted from the origin $x = 0$ at the epicenter of the occurrence, the location of which is not known and not shown on the chart, let us find the connection between h and the distance p from x_1 to x_m, and the distance q from x_m to x_2:

$$x_1 - x_m = p; \quad x_1 = p + x_m;$$
$$x_m - x_2 = q; \quad x_2 = -q + x_m,$$

from which we obtain

$$x_1 + x_2 - 2x_m = p - q.$$

In accordance with the properties of the roots of equation (9.5):

$$x_1 + x_2 = 12x_m,$$

and consequently

$$10x_m = p - q.$$

It follows from equation (9.5) that [illegible] $= -$ [illegible]. Substituting the values of x_1 and [illegible], and, [illegible] (−q), we obtain

$$h = 0{,}7\sqrt{pq - 0{,}11\,(p - q)^2}. \qquad (9,6)$$

The equation [illegible] of the sphere does not depend upon the [illegible] profile passing through the epicenter. [illegible] profile may be used. With [illegible] curve is symmetrical [illegible], [illegible] formula for the case of direct [illegible], [illegible] distance from the point at which [illegible], to the point [illegible] $Z = 0$.

In the case of symmetrical Z (or ΔT) curves, when the anomaly is highly elongated, the equations developed by the present author (see Logachev, 1951) for anomalies represented solely by positive Z (or ΔT) values, corresponding to vertical strata of marked distribution in depth, large area, and a thickness of 2b, have justified themselves in practice:

$$h = \frac{x_2^2 - x_1^2}{2x_1}; \qquad 2b = 2\sqrt{x_1^2 - h^2};$$

$$I = \frac{Z_{max}}{4\,\mathrm{arctg}\,\frac{b}{h}},$$

in which x_1 is half the distance between points at which $Z = \frac{1}{2}Z_{max}$, and x_2 is half the distance between points at which $Z = \frac{1}{4}Z_{max}$.

Where there is clearly defined asymmetry of the Z (or ΔT) curves, induced by inclined dip or oblique magnetization of a stratum of great length and great distribution in depth, it is desirable to break the curve up into a symmetrical portion (the curve of the arc tangent) and the asymmetrical (the curve of the logarithm), with subsequent application to the curve of the arc tangent, of the equations adduced above. The criterion indicating that this approach may be used is the presence of a zone of negative Z (or ΔT) values, on the side of the positive values having the maximum gradient.

From the relationship of the ordinates of the curves for the arc tangent and the logarithm at some specific point we calculate the angle of dip of the stratum, which in the general case is modified by a magnitude corresponding the deviation of the vector of intensity of magnetization from the vertical.

The techniques for making these determinations are provided in detail in the textbook literature (see Logachev, 1951). It need only be added that the best criterion for determining the applicability of the given method of solution to a specific anomaly and for finding the origin of the coordinates relative to which the Z (or ΔT) curve is divided into curves of half the sums and half the differences is the curve for the total vector $T_a = \sqrt{Z_a^2 + H_a^2}$. If the given anomaly corresponds to the condition that there be an inclined stratum of great distribution in depth, then the T_a curve will be symmetrical, and the origin of the coordinates will be at point $T = T_{max}$.

Symmetrical Z (or ΔT) curves with negative values on both sides of the band of positive values provide the basis for the assumption that there be a vertical stratum of limited distribution in depth, a special case of which is a body approximating a cylinder in form.

In the former case the problem is resolved simply, if the thickness of the body is less than the depth of occurrence and significantly less than its dimensions along the dip. The following equations are among those which may be used:

$$R = 0{,}7\frac{x_1^2}{x_2}, \qquad l = \sqrt{R^2 - x_1^2}; \qquad h = R - l,$$

in which R is the depth of occurrence of the center line of the stratum, 2 l is the parameter along the dip, h is the depth of the top of the body, x_1 is 1/2 the distance between points at which $Z = 0$, and x_2 is 1/2 the distance between points at which $Z = 1/2 Z_{max}$. The equation for determining R is arrived at by converting the analytic expression for the abscissa of the point at which $Z = 1/2 Z_{max}$ and calculation of its approximated value $x_2 = \pm \frac{R^2 - l^2}{R\sqrt{2}}$. If the section of the body in the plane perpendicular to the long axis is practically equiaxial (that is, circular), the center of the circle is found easily by means of the equation $R = x_1$.

Asymmetrical Z (or ΔT) curves with negative values on both sides of the positive values, repeating themselves on a sufficient number of trip routes and thus indicating a body of large size, represent an inclined stratum of small distribution in depth or an obliquely magnetized body, the axes of the cross-section of which are of a single order of magnitude, a special case of this being an obliquely magnetized cylinder.

The solutions found by the author for the cases under discussion (see Logachev, 1951) may be of very limited applicability because of the fact that in practice we are rarely successful in finding the points necessary for utilization of the formulas advanced.

Below we shall recommend a solution for the problem of inclined strata by means of derivative curves. As far as the Z (or ΔT) curves over an obliquely magnetized cylinder of circular section are concerned, the following method is used to calculate the center of the vertical section and magnetic moment of a cylinder core from the initial cylinder perpendicular to its axis and with a height equal to the unit employed for measurement of length.

In Section 4 we found that the abscissa of Z_{max} is determined by the equation

$$x_m = -\frac{1}{3} h \operatorname{tg} \beta, \qquad (9,7)$$

in which β is the angle of inclination from the vertical of the vector of magnetic intensity.

Let us find the point of intersection of the Z curve with the x axis, for which purpose we assume $Z = 0$ in equation (4.11). Thus we obtain the equation

$$h^2 - x^2 - 2hx \operatorname{tg} \beta = 0. \qquad (9,8)$$

Substituting the value of tg β from equation (9.7) into equation (9.8), we obtain

$$x^2 - 6xx_m - h^2 = 0. \qquad (9,9)$$

From this it would be possible to find h if the graph showed the origin of the coordinates corresponding to the epicenter of the section of the cylinder. However the graph only provides the distance between the values of Z_{max} and Z_{min}, which we designate as p and q. Thus we obtain

$$x_1 - x_m = p; \quad x_m - x_2 = q.$$

On the basis of the reasoning advanced in examining the question as to the location of the center of an obliquely magnetized sphere we arrive at

$$h = \sqrt{pq - \frac{5}{16}(p-q)^2}. \qquad (9,10)$$

The depth of occurrence of the axis of the cylinder of circular section may also be found by separating the asymmetrical curve Z, or ΔT, into symmetrical and asymmetrical parts.

Employing equation (r.11), describing the field above an obliquely magnetized cylinder, let us remove the symmetrical portion, plotting curves for the half sums and half differences of Z in accordance with the values of Z at points equidistant from the origin of the coordinates:

$$Z_1 = \frac{1}{2}\,[Z(+x) + Z(-x)] = 2M\cos\beta\frac{h^2 - x^2}{(h^2 + x^2)^2}; \qquad (9,11)$$

$$Z_2 = \frac{1}{2}[Z(+x) - Z(-x)] = 2M\sin\beta\frac{2hx}{(h^2 + x^2)^2}. \qquad (9,12)$$

Equations (9.11) and (9.12) differ from equations Z and H over a cylinder on direct magnetization only by the presence of constant multipliers, sin β and cos β, and consequently, the shape of the Z_1 and Z_2 curves may be employed to find the depth of occurrence h.

The axis of symmetry in terms of which the curves of half sums and half differences are developed, is found by erecting the curve for the total T vector, for which it is necessary to calculate the H curve at the outset on the given Z. The location of the T curve maximum determines the origin of the coordinates in terms of which the Z_1 and Z_2 curves are plotted.

In certain cases, separation of the symmetrical portion of the curve is possible also for inclined strata with small distribution in depth and little thickness, 2b, relative to depth of origin.

If magnetization coincides in direction with the dip of the stratum, the expression for Z takes on the following appearance:

$$Z = 2I2b\left[\frac{h_1}{h_1^2 + (x + l\cos i)^2} - \frac{h_2}{h_2^2 + (x - l\cos i)^2}\right], \qquad (9,13)$$

in which h_1 and h_2 are the depths of the upper and lower boundaries of the stratum, 2 l is the length along the dip, and i is the angle of dip.

By examining cases in which the i angle differs from 90^{o} by not more than 30^{o}, it becomes possible to simplify expression (9.13) after it has been reduced to the common denominator, the relatively small terms of the latter, containing $\cos^2 i$, being eliminated.

Thereafter the symmetrical and asymmetrical portions of the Z curve take on the appearance

$$Z_1 = \frac{1}{2}[Z(+x) + Z(-x)] = 2M\sin i\frac{h_1h_2 - x^2}{(h_1^2 + x^2)(h_2^2 + x^2)}, \qquad (9,14)$$

$$Z_2 = \frac{1}{2}[Z(+x) - Z(-x)] = 2M\cos i\frac{x(h_1 + h_2)}{(h_1^2 + x^2)(h_2^2 + x^2)}, \qquad (9,15)$$

in which $M = 2b \cdot 2\,lI$.

Equations (9.14) and (9.15) represent curves similar to curves Z and H over a vertical stratum of the same section, the centers of sections through inclined and vertical strata coinciding. The ratios of similitude are expressed accordingly by the factors sin i and cos i.

The origin of the coordinates is set at a point constituting the projection of the center of the cross-section along the line of observations. This point may be found by projecting the T curve, which will have its maximum at the origin of the coordinates.

Calculation of the depth of origin of large massifs, the field of which is characterized by sharp variation along the borders of the massif, may be carried out on the basis of the Z (or ΔT) curve as follows. If the extreme values of Z_{max} and Z_{min} are equal and are equidistant, $x_э$, from the point at which $Z = 0$, the x abscissas will be related to depth h_1 of the upper, and to depth h_2 of the lower surface in accordance with the following expression

$$x_э^2 = h_1 h_2. \qquad (9,16)$$

In order to derive the second equation, which relates the h_1 and h_2 depths to the abscissas of any points whatever on curve Z by means of a simple equation, we set up an equation in the form $Z = 1/2Z_{max}$, employing the Z curve as an analytical expression. The simple appearing equation derived therefrom is solved together with equation (9.16), from which we obtain

$$h_2 - h_1 = \frac{1}{x_э}\sqrt{(x_к^2 + x_э^2)(x_к^2 + x_э^2 - 4x_к x_э)} \qquad (9,17)$$

in which $\pm x_к$ designates the abscissas of the points at which $Z = \pm{}^1/_2 Z_э$. There will be 2 such points in the zone of positive and negative values, while derivation of $h_2 - h_1$ in accordance with equation (9.17) is equally possible for any of them.

Knowing the product and difference between depths h_1 and h_2, it is easy to calculate the value of each magnitude separately.

Study of equation (9.17) shows that the values $x_к^2 + x_э^2$ and $4x_к x_э$ are very similar, in view of which fact the given method of derivation may be recommended with the qualification that the zero line must be successfully determined and the measurements made to high accuracy.

In this connection the section following is devoted to presenting a method of comparing the curves obtained by practical observation with the theoretical for bodies of known section. Further, examination is made of an analytical method founded on employment of the derivatives of the curves.

It has not proved possible to compile formulas for the calculation of depth of occurrence for the case of contact on the incline. Below we advance a graphic method of finding the depth and angle of incline.

Employing the familiar equation for Z over the edge portion of magnetic rocks (Logachev, 1951, equation 147, cf.), we find the abscissas for the extreme values of Z by the usual method, that is, on the assumption that $\frac{\partial Z}{\partial x} = 0$, obtaining the equation

$$x_э^2 - (h_2 - h_1)\, x_э \operatorname{ctg} \alpha - h_1 h_2 = 0, \qquad (9,18)$$

from which it follows that the derivation of the abscissas of the extreme values x_1 and x_2 both over perpendicular and inclined planes of contact rock is subject to the equation

$$x_1 x_2 = - h_1 h_2. \qquad (9,19)$$

The nomogram (Figure 28) consists of 2 systems of curves with constant $h_1 h_2$ value. One system represents the connection between $\frac{Z_{max}}{Z_{min}}$ and $\frac{x_1 - x_0}{x_0 - x_2}$ at given h_2-h_1 values, and an α angle varying uninterruptedly from a slight angle to 90°, while the other system represents the connection between the same magnitudes at given α and an h_2-h_1 changing uninterruptedly from the maximum to the minimum.

The magnitude x_1-x_0 represents the distance from the point at which $Z = Z_{max}$ to the point at which $Z = 0$, while $x_0 - x_2$ is the distance from the point where $Z = 0$ to that where $Z = Z_{min}$. In the compilation of the nomogram it is taken that $h_1 h_2 = 100$.

The nomogram has been compiled only for angles in which $\alpha < 90°$ and, correspondingly, for the ratio $\frac{Z_{max}}{Z_{min}} < 1$. However, if the ratio under observation is greater than unity, it is necessary, in order to make use of the suggested nomogram, to regard Z_{max} as Z_{min} and vice versa (that is, to change the signs of the ordinates of the curves). After the decision for the inverted curve has been found it is necessary only to take into consideration the fact that the angle of inclination of the plane of contact will be $180 - \alpha$, in which α is a value taken from the nomogram along the inverted Z curve.

This nomogram is used as follows.

Let us find on the nomogram a point the ordinate of which is the $\frac{Z_{max}}{Z_{min}}$ ratio taken from the Z curve and the abscissa is the $\frac{x_1 - x_0}{x_0 - x_2}$. Now let us establish which curves from the $(h_2 - h_1)$ set and the α set pass through it and are closest to it. The values $h_2 - h_1$ and α, corresponding to the curves found, will be the solutions desired, $h_2 - h_1$ being located in the same conventional units in which $h_1 h_2 = 100$ is given. Knowing the depth differential $h_2 - h_1$ and the product of these depths, we find the value of the depths in conventional units. To convert the conventional units into a given unit of length, we obtain from the graph the distance between the extreme values $d = x_1 - x_2$ in meters (or kilometers) and compile an equation for the calculation of the transitional factor, μ:

$$\frac{d}{\mu} = 2\sqrt{\left[\frac{1}{2}(h_2 - h_1)\operatorname{ctg}\alpha\right]^2 + h_1 h_2}$$

The right side of this last equation is compiled as the difference between the roots of the equation (9.18). Calculating the μ factor, we convert the h_1 and h_2 values into a specific system of units.

In employing the graphic method of solution in the proposed variant it is necessary to bear in mind that only 3 points are employed in practice, while the position of the middle point, where $Z = 0$, depends upon the choice of the normal field. Limited employment of the points on the curve has a powerful effect on the reliability of the calculated characteristics of occurrence, in view of which the proposed method can be used only for an approximated determination of depths. More precise methods are examined below.

The cases under examination embrace all the primary forms of the simplest bodies for which the simplest formulas may be applied for calculation of the characteristics of occurrence directly in accordance with the values of the Z (or ΔT) fields. It might be possible to add formulas for calculating the components of occurrence of bodies similar in form to a vertical rod and to a horizontal layer of limited thickness. However the need for formulas of this type is hardly ever encountered in practice. In the second place they may readily be derived in a fashion analogous to those presented in the textbooks. It is necessary to remark that the formulas advanced for each case under examination constitute one of the possible variants. Here we adduce either those that find application in practice or those that are simpler relative to the equations presented above.

10. Determination of Characteristics of Occurrence by Comparing the Measured Field with the Theoretical Fields of Bodies of Simple Shape

Determination of the characteristics of occurrence of magnetized bodies by comparison of the observed field with fields of various shapes calculated theoretically would be the simplest method of all, if it were possible to present in a reasonably limited number of graphs all the variety in the shapes of bodies and their position in space relative to the direction of the magnetized field.

At present, summary graphs of the magnetic fields of various bodies of the simplest forms have been published only for the cases of vertical dip and vertical magnetization, that is, for anomalies represented by symmetrical Z curves. This last circumstance very strongly limits the possibilities for the practical employment of the diagrams now at hand (more frequently termed templates). A certain expansion in their zone of application is being effected by the averaging of the right and left arms of the assymetrical curves, which inevitably carries with it an increase in the error of the values found for the characteristics of occurrence.

V. A. Bugaylo, N. A. Ivanov, T. N. Simoneko (Roze), Yu. P. Tafeyev, etc, have worked on the development of these guide graphs.

N. A. Ivanov (cf. 1951) has developed such a diagram for elliptical cylinders (Figure 29), for a compressed ellipsoid of rotation (Figure 30), and for vertical strata of infinite distribution in depth (Figure 31).

N. A. Ivanov's graphs are employed as follows.

The curve observed in practice along a line transverse to the trend of the body (or, where 3-dimensional bodies are concerned, along a line passing above the center of the occurrence), is laid out on the scale of the graph. This means that Z_{max} and the distance from Z_{max} to Z, equal to $1/2Z_{max}$, are taken to be such as they are on the graph employed. The Z curve thus laid out (or the ΔT curve, if it is close to the symmetrical) is compared to the curves drawn on the 3 given nomograms, to the first or third in the case of highly elongated anomalies, and to the second if the contours of the anomalies in the isolines appear to be nearly circular. If the practical curve in the direction perpendicular to the trend, and, if we are dealing with an ellipsoid, that passing through the epicenter, coincides with one of the curves depicted, further operations are performed to determine the depth.

(a) The case in which the practical curve coincides, when rendered in the scale of the nomogram, with one of the curves for the elliptical cylinder. The index of this curve is $n = z/q$, and $z = nq$ in conventional units. The factor of conversion is equal to the number of meters (or other units) of distance from Z_{max} to the point at which $Z = 1/2Z_{max}$. If the stratum is thin relative to its distribution in depth, then $\underline{m}(z-q)$ may to a certain approximation be taken as the depth h of the upper limit of the stratum. In this case the true depth of h must be somewhat smaller.

(b) In the case of coincidence between the practical curve and one of the curves in Figure 30, on which the curves are given for ellipsoids of rotation, that is, when the anomaly is represented on the chart by isometric contours, the depth of the center of the occurrence is determined in the same manner as in the preceding instance.

(c) Should the practical curve coincide with one of the curves in Figure 31, we find c by the supplementary graph in accordance with the corresponding value of $n = h/c$ (the ratio of the depth of the upper edge of h to the horizontal thickness of the stratum c), and then we find $h = nc$ in conventional units. The factor of conversion μ

is determined in the same manner as in the first case examined above.

Yu. P. Tafeyev (1950, cf) compiled a nomogram for locating the parameters of occurrence of vertical bodies of large long axis, and those of the simplest triaxial bodies on a logarithmic scale, thus simplifying the process of comparing the practical curve with the theoretical (Figure 32).

The plotting of the nomogram and the manner in which it is used consist of the following.

The Z maximum is taken to be equivalent to a conventional unit, the depth of the top of the vertical stratum to be unity (h = 1), and all linear dimensions of the body and coordinates of the points are expressed in units of depth. Under these conditions, the field of a vertical stratum 2p thick and of large distribution in depth takes on the following appearance

$$\frac{Z}{Z_{max}} = \frac{\operatorname{arctg}(x+p) - \operatorname{arctg}(x-p)}{2\operatorname{arctg} p},$$

and the field of a thin vertical stratum, in which the distance between the pole lines is q, appears as follows

$$\frac{Z}{Z_{max}} = \frac{1+q}{q}\left[\frac{1}{1+x^2} - \frac{1+q}{(1+q)^2+x^2}\right].$$

Curves with differing p and q values are depicted on the nomogram in logarithmic scale. The subscripts of p and q on the nomogram signify h units.

The nomogram, on translucent paper, is laid over the Z curve and moved parallel to the coordinate axes until a point is reached providing the best coincidence between one of the theoretical curves and the Z curves. The point of intersection between the axis of the abscissa of the Z curve with the line of the h depth on the nomogram yields the depth of occurrence in whatever units have been used to lay out the Z curve. That curve of the nomogram which coincides with the Z curve is used to determine the thickness of a body of marked distribution in depth, or the vertical dimensions of a stratum of limited thickness and relatively limited distribution in depth.

In connection with the fact that aeromagnetic survey often reveals changes in field corresponding to the boundary of large massifs of rocks of varying properties, the present author has compiled a nomogram with thich to determine the depth of the upper and lower boundaries of the magnetic massif for the case in which the Z (or ΔT) curve has equal absolute values for Z_{max} and Z_{min}, while the distances representing the extreme values thereof, x_e , from the Z = 0 point are identical throughout (that is, a case of vertical contact).

The resultant nomogram (Figure 33) is based on equation

$$x^2{}_e = h_1 h_2.$$

Taking $h_1 h_2 = 100$, we find $x_e = \pm 10$. The curves have been calculated for various vertical thicknesses equivalent to the differences in depth, to wit, 99, 48, 30, 20, 10, 5, and 2. All the curves are rendered in accordance with a scale on which Z_{max} numerically equals x_e.

In order to make use of this nomogram, one plots the Z or (or ΔT) curve, based on equal extreme values, employing the scale used for the nomogram, and then lays the nomogram (which is on transparent paper) over this curve. We find $h_2 - h_1$ on the basis of the coincidence with one of the theoretical curves. Given $h_1 h_2 = 100$, we find the values of h_1 and h_2 in conventional units. To convert them to specific units of length we find the conversion factor from the expression $d:x_e$ where d is the distance in meters or kilometers between $Z = 0$ and $Z = Z_{max}$, as derived from the given curve, while $x_e = 10$. It is obvious that the set of theoretical curves for bodies of simple shape and direct magnetization may be compiled in various variants. Such curves may readily be employed for purposes of comparison with practical curves which are symmetrical or consist of 2 branches, the ordinates of which differ only in sign.

The majority of the anomalies found in nature do not satisfy this last requirement. Therefore successful and broad application of the method of comparison of practical curves with theoretical curves calculated for known objects require that means be found to depict the sets of asymmetrical curves for groups of bodies differing in form.

11. Calculation of Characteristics of Occurrence by Values of the Anomalous Field at Various Levels

The fact that it is possible to measure experimentally or to derive mathematically the anomalous field at various levels greatly simplifies the determination of characteristics of occurrence and makes it possible to check the accuracy of hypotheses as to the shapes of bodies in accordance with changes in the field related to the altitude of the plane of observation.

In making use of the values of the field at various altitudes for calculation of the characteristics of occurrence one must give preference to the calculated and not the experimentally measured values at the new level, as unavoidable errors of determination of the coordinates of the aircraft are capable of resulting in wide errors in calculating the characteristics of occurrence.

Calculations of the field at a new and higher level may be carried out to any degree of accuracy required in practice, to be in accord with the accuracy of the initial data, the cost of the mathematical work being considerably lower than that of experimental measurement.

Only when it is necessary to determine the field in a plane lower than that in which the measurements have been carried out in the initial survey are direct measurements more valuable (if topographical conditions permit them to be made), as determination of the field by analysis below the given plane presents the problem of the superimposition of significant errors.

The practical value of data on the field at various levels, in cases where there are well founded hypotheses as to the shape of the body, consists in the fact that the possibility arises of compiling very simple equations for the calculation of the geometric parameters of the body. Let us clarify this by an example.

It is known that calculation of the characteristics of occurrence of an inclined stratum of limited thickness and distribution by depth, based on measurements in a single plane, presents great difficulties in view of the fact that the development of simple equations makes it necessary to use on the profile, points of field values which do not always occur in nature (see Logachev, 1951, chapter 44). However, if we are possessed of means of calculating the field at a new level, it becomes possible, for example, to make use only of the distance between those points at which Z = 0. If we designate this distance as d_1 at the lower level, where the field has actually been measured, as d_2 at level h+a, and as d_3 at level h+b, we compile 3 equations

$$d_1^2 = \operatorname{cosec}^2\alpha\,(h^2 - l^2 \sin^2\alpha),$$

$$d_2^2 = \operatorname{cosec}^2\alpha\,[(h + a)^2 - l^2 \sin^2\alpha],$$

$$d_3^2 = \operatorname{cosec}^2\alpha\,[(h + b)^2 - l^2 \sin^2\alpha].$$

in which h is the depth of occurrence of the midline of the stratum, 2l is its length along the dip, and α is the stratum's angle of inclination relative to the horizon.

Solving this system of equations, we find:

$$h = \frac{1}{2}\frac{(d_3^2 - d_1^2)a^2 - (d_2^2 - d_1^2)b^2}{(d_2^2 - d_1^2)b - (d_3^2 - d_1^2)a}.$$

If h is known, finding 2 l and α is simple and, with these, the product of the intensity of magnetization by the thickness of the stratum. Many other variants for the solution of this problem may be proposed if other points on curve Z or curve H are to be employed.

Analogously it is possible to employ the data for the field at various levels for any other body of given shape in a variety of variants which are not dealt with here because of the ease with which these variants may be arrived at. Let us limit ourselves to examining 2 cases which are capable of being applied directly to the fields observed and which are particularly important in the utilization of the first and second derivatives of Z (or ΔT) to calculate the characteristics of occurrence of magnetized bodies in the face of complex anomalies.

Now let us examine the Z field of an inclined stratum of great extent and great distribution in depth, in which thickness 2b is small relative to depth of occurrence h. Ignoring the second powers of the b/h ratio in the familiar expression for the field, in this case we obtain a simpler equation:

$$Z = I\sin\alpha\left(2\sin\alpha \operatorname{arc\,tg}\frac{2bh}{x^2+h^2} + \cos\alpha \ln\frac{x^2+h^2+2bx}{x^2+h^2-2bx}\right). \qquad (11,1)$$

Applying to equation (11.1), the formulas for the analysis of the arc tangent and the logarithm, we obtain

$$Z = 4Ib\sin\alpha\frac{h\sin\alpha + x\cos\alpha}{x^2+h^2}. \qquad (11,2)$$

To find the maximum and minimum of the Z curve, let us write $\frac{\partial Z}{\partial x} = 0$:

$$x_n^2 + 2x_n h \operatorname{tg}\alpha - h^2 = 0,$$

$$x_n = -h\operatorname{tg}\alpha \pm h\sec\alpha,$$

$$x_{max} = h\frac{1-\sin\alpha}{\cos\alpha}. \qquad (11,3)$$

Substituting the value of x_{max} in equation (11.2), we obtain

$$Z_{max} = 2Ib\frac{1}{h}\,\frac{\sin\alpha\cos^2\alpha}{1-\sin\alpha} = 2Ib\frac{1}{h}\sin\alpha\,(1+\sin\alpha). \qquad (11,4)$$

It follows from equation (11.4) that for a specific body

$$hZ_{max} = c,$$

where c is the magnitude of the constant for the given body.

In order to find h we locate Z_{max} at a new level, differing from the first by a known magnitude of Δh. Designating Z_{max} at the initial altitude by Z_1, and at the new altitude by Z_2, we obtain

$$hZ_1 = (h + \Delta h)Z_2,$$

from which we derive

$$h = \frac{Z_2}{Z_1 - Z_2}\Delta h. \qquad (11,5)$$

In order to determine the angle of slope α which differs in the general case from the real angle of incline due to the deviation from the vertical of the vector of the magnetized field in the cross-section under examination, let us employ the abscissas x_1 for Z_1 and x_2 for Z_2. As the origin of the coordinates in the profile is unknown, let us employ the difference $d = x_1 - x_2$, and on the basis of (11.3) let us write:

$$d = \frac{1-\sin\alpha}{\cos\alpha}\Delta h, \qquad (11,6)$$

from which we find

$$\sin\alpha = \frac{\Delta h^2 - d^2}{\Delta h^2 + d^2}.$$

If there is a sharp drop $\Delta h \gg d$, the following formula will suffice to adequate accuracy

$$\sin\alpha = 1 - 2\left(\frac{d}{\Delta h}\right)^2. \qquad (11,7)$$

In order to find the abscissa of the peak of the stratum, let us give our attention to the fact that the $\frac{d}{\Delta h}$ ratio is according to equation (11.6) a constant so that consequently the line connecting the abscissas of the Z_{max} points at various levels is a straight line passing through the top of the stratum. Then the point of intersection of this line with a horizontal line drawn at the h depth that has been found, will determine the location of the top of the stratum at the given section. Figure 34 illustrates the Z curve above the inclined stratum, the calculated Z curves at 2 altitudes, and the graphic determination of the top of the stratum. The angle of dip of the stratum, which is 60°, is calculated by means of the angle β.

Let us examine the field of an indirectly magnetized cylinder. In chapter 4 above we have set forth the method of finding the abscissa of a point at which the Z curve attains its maximum value. Substituting the value of the abscissa (4.13) in expression Z (4.11), we find the equation for Z_{max}:

$$Z_{max} = \frac{2M}{h^2}\,\frac{\left(1-\frac{1}{9}\operatorname{tg}^2\beta\right)\cos\beta + \frac{2}{3}\operatorname{tg}\beta\sin\beta}{\left(1+\frac{1}{9}\operatorname{tg}^2\beta\right)^2} = \frac{2M}{h^2}f(\beta), \qquad (11,8)$$

in which β is the angle of inclination from the vertical of the vector of intensity of magnetization.

It is obvious that at the new altitude h+ Δh, the value of Z_{max} will be

$$Z'_{max} = \frac{2M}{(h+\Delta h)^2}f(\beta). \qquad (11,9)$$

Solving the latter 2 equations jointly for h, we obtain:

$$h = \frac{\sqrt{Z'_{max}}}{\sqrt{Z_{max}} - \sqrt{Z'_{max}}} \Delta h. \qquad (11,10)$$

In order to find angle β, let us employ the differences between the abscissas of points $x_1 - x_2$, where x_1 is the abscissa of Z_{max} at the level of origin and x_2 is the abscissa of Z_{max} at the $h + \Delta h$ level. On the basis of equation (4.13), we find

$$x_1 - x_2 = \frac{1}{3} \Delta h \, tg \beta,$$

from which we derive

$$tg \beta = 3 \frac{x_1 - x_2}{\Delta h} \qquad (11,11)$$

or

$$tg \alpha = \frac{\Delta h}{3(x_1 - x_2)}. \qquad (11,12)$$

in which α is the angle of inclination of the vector of intensity of magnetization.

The location of the center of the cross-section of a cylinder of circular section is arrived at by finding the point of intersection of a horizontal line on the calculated depth h, with a straight line passing through the abscissas of the Z_{max} points at various levels.

Figure 35 illustrates the given curve Z over a cylinder of circular section with oblique magnetization, the derived curve Z at altitude $h + \Delta h$, and the center of a cylinder of circular section derived in the manner indicated, as well as the position of the vector for intensity of magnetization I. The β angle representing deviation of the I vector from the vertical is 3 times as large as the angle ϕ, which is formed by a straight line passing through points x_1 and x_2 and a vertical.

It is obvious from the method of resolving this problem that when experimental curves are employed at various altitudes the errors in relating the measurements to precise loci along the survey route may produce very large errors in calculating the characteristics of occurrence, particularly in deriving the angle of dip and the location of the upper edge of the stratum or the center of the section of a cylinder. We therefore recommend employment of calculated, not measured, values of Z (or ΔT) at a new level.

12. Calculation of Depth and Other Characteristics of Occurrence of Magnetized Bodies by the Gradients of the Z or ΔT Curves

Derivation of the characteristics of occurrence of magnetized bodies by means of the higher derivatives of magnetic potential has the advantage that, in a case of superimposition of the magnetic fields of a number of bodies in near proximity, the higher derivatives of the magnetic potential of each body decline with increased distance more rapidly than the first derivatives. Thanks to this fact, the effect of the fields of neighboring bodies on the field of a given body declines and the possibility of deciphering the anomaly increases.

The analytical expressions for the second derivatives of magnetic potential, which are readily obtained by differentiating the expressions for the Z or H fields (and also for ΔT) for a body of given form along a given coordinate axis, are very complicated. It is easy to convince oneself of this if for example we seek $\frac{\partial Z}{\partial x}$ or $\frac{\partial Z}{\partial h}$ for an instance of oblique magnetization of a vertical stratum of considerable thickness. This consideration has created such great difficulties that the idea, advanced long since, of utilizing the higher derivatives of the magnetic potential have not found practical application.

Let us find an approximated solution for the problem on the basis of geometrical concepts of various higher derivatives, to wit,

$\frac{\partial Z}{\partial x}$ and $\frac{\partial^2 Z}{\partial x\, \partial z}$ (or the same derivatives of H and ΔT).

In Section 7 we have already employed the fields of different bodies, developed in our concept as a consequence of the assumed displacement of the real body along the x axis by the distance Δx, and the "subtraction" of the real body from the displaced one. The result is the development of imaginary bodies formed from the side surfaces of the real ones, and of surfaces parallel thereto, displaced by a distance Δx (see Figure 18). On the one hand we obtain an imaginary body with excess, and on the other, with inadequate, magnetic mass. In other words one of the imaginary bodies retains the intensity of magnetization of the real body, while in the other the vector of intensity of magnetization retains its magnitude but changes in direction to its opposite. The foregoing holds for strata not only with parallel side surfaces but with convergent and divergent surfaces as well.

Plotting the derivative $\frac{\partial Z}{\partial x}$ graphically on the known Z field over a magnetized stratum of large horizontal thickness, we obtain a curve with clearly defined maximum and minimum $\frac{\partial Z}{\partial x}$, corresponding to the 2 imaginary strata. The mutual effect of the field of a single imaginary stratum upon that of another will be the smaller, the further apart they are or in other words the greater the horizontal thickness of the body expressed in units of depth of occurrence of the upper edge. The approximateness of the solution of the problem lies in the fact that one assumes complete absence of mutual influence by the field of one imaginary stratum on the field of the other. This makes it possible to employ relatively simple formulas expressing the field intensities of isolated bodies instead of complex formulas expressing the sums of the fields of 2 imaginary bodies.

Investigation of the applicability of this method shows that, in order to obtain results with an error of less than 5% by means of theoretical curves of an inclined stratum of infinite distribution in depth, the horizontal thickness of the stratum must exceed the depth of occurrence of the upper edge approximately 10-fold.

If the distribution of the bodies by depth is limited, this requirement is reduced, as in this case the Z (or ΔT) field above imaginary strata of limited thickness declines more rapidly with increase in distance along the ξ axis, and consequently the field of one stratum affects the Z_{max} magnitude over the other to a lesser degree. This provides a considerable expansion of the zone of applicability of the method of calculating depth by the first derivative, $\frac{\partial Z}{\partial x}$ or $\frac{\partial(\Delta T)}{\partial x}$. However, if the vertical thickness of the body should be small relative to the depth of occurrence, particularly when it is smaller than the depth of occurrence, the method under examination becomes inapplicable, as the field of imaginary strata sectioned along the edges of a real body of limited vertical thickness will approximate the field of a cylinder and not that of a stratum of limited horizontal thickness and considerable distribution in depth.

The most appropriate objects for employment of this method are areas with clearly defined stepwise change in the Z (or Δ T) field, indicating the dividing line between large geological forms. Aerial magnetic survey encounters such changes in field with considerable frequency.

If the general nature of the magnetic field permits us to draw the conclusion that a given magnetic anomaly is produced by a body the dimensions of which, transverse to its trend and its distribution in depth, exceed several-fold the depth of occurrence of the upper edge, then the curves (including positive and negative branches) obtained as a result of graphic differentiation may be regarded as curves whose analytical expression is presented by equation (11.1). Consequently equations (11.5) and (11.7) are applicable thereto for purposes of determining the depth of the top and the angle of inclination.

We know that curve $\frac{\partial Z}{\partial x}$ does not depend upon the level of the normal field selected and consequently that the given method of calculating the depth and angle of dip of the stratum does not depend upon errors in the choice of the normal field for the curves of origin Z or ΔT. This is one of the advantages inherent therein, relative to methods of calculating depth directly from the curves of field intensity.

If the problem is limited solely to calculation of the depth of occurrence of the upper edge of magnetized bodies, and determination of the angle of dip is not required (a problem which arises, for example, in the plotting of structural maps of the base of platform regions), it is unnecessary to plot the $\frac{\partial Z}{\partial x}$ or $\frac{\partial(\Delta T)}{\partial x}$ curve. For the purpose in question it is entirely sufficient merely to find the point of inflexion along the portion of the Z (or ΔT) curve selected and to determine the increase in the curve in the region of inflexion in the interval between points x_1 and x_2 (Figure 36). Knowing that at the new altitude the maximum gradient undergoes insignificant displacement, we assume that the maximum gradient at the new altitude will be in the same interval between points x_1 and x_2. Therefore we calculate the Z (or ΔT) field at altitude Δh relative to the starting point at only these 2 points. The difference between the Z (or ΔT) values at points x_1 and x_2 at the former and latter altitudes will correspond to the Z_1 and Z_2 values in equation (11.5). The interval determined by abscissas x_1 and x_2 embraces the steepest

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portions of the Z or ΔT curve. It makes no difference what units are employed to measure the gradient. The depth is arrived at in the same units as those in which Δh is given.

Let us illustrate the use of the method by means of a practical example. Figure 37 shows the ΔT field along a small section taken from a 1:200,000 map in which the ordinates of the curves are depicted in a scale of 100 γ per cm. Three wells have been sunk in this section. The depth of the crystalline foundation is shown on the chart.

The width of the anomalous field, represented by positive ΔT values, exceeds 10 km. Information is available to indicate that the depths are about one km. Thus we are justified in using the method under examination. However it is difficult to use curves to calculate depths on this scale, as the experience accumulated in calculating a field at a new altitude by means of a nomogram (see Figure 12) indicates that the new altitude must show as not less than one cm on the drawing, meaning that with the given scale it must not be less than 2 km. When a field is recalculated at so great an altitude the effects of magnetic fields quite a distance away are felt and this is undesirable. Therefore to calculate depth we draw the ΔT curves in a scale of 1:50,000, also increasing the scale of the ordinates to 50 γ per cm, with the purpose of obtaining a more exact calculation of the field at the new altitude. In general it is a convenience always to set the linear scale in such fashion that the new altitude is represented by one cm. It goes without saying that an increase in the scale carries with it a proportional increase in the errors in the original.

In order to maintain the constant one-centimeter height it is more convenient to set up the nomogram in a new form (Figure 38).

For convenience of calculation each third vertical line is drawn heavier. The ninth interval is divided in 2 by a broken line. If one so desires, the value of the middle ordinate may be taken off immediately along the entire interval, or the mean value may be determined at each half interval, and the average taken accordingly. The tenth interval ends at infinity. For this reason broken lines are used to indicate the first 3/5. Each of these represents an angle of 1.8°. In each of these the average value of the ordinate is divided by 5. Only then is it added to the total sum. The nomogram is symmetrical. The average ordinates on the right and left are totaled (with allowance for what was stated above relative to fractions of intervals) and the total is divided by 20.

Figure 39 shows the upper ΔT curve of Figure 37 in enlarged scale. It has been related to the level of the survey at altitude h, including the depth of occurrence and a flight altitude of the order of 100 m. The new level, at an altitude of 500 m, at which the ΔT_1 value is calculated, is depicted by a broken line drawn in accordance with the established scale. The broken curves I and II depict the curves of the ΔT gradient of the right and left branches of the ΔT curve at altitudes h and h+500 m (the symbols for gradient to right and left are taken as positive).

The depths are calculated in accordance with the right and left branches of the curve, in accordance with equation (11.5): $h=\frac{15{,}5}{23-15{,}5}500=1030\,м$;

$$h=\frac{27}{40-27}500=1040\ м.$$

Eliminating flight altitude, which is 100 m, we obtain the depths along the right and left branches, 930 and 940 m. Further, we find the edge of the magnetized bodies by means of the intersections of lines determining the depth of occurrence, with lines connecting the points with maximum gradients at the h and h+500 m levels, and thereafter in accordance with equation (11.7) we find the angle of incline of thestrata. In the general case the angle of dip of the slope includes the angle of inclination from the vertical, of the vector of intensity of magnetization, but in the given case, in which the bodies follow a course virtually along the meridian course, this angle is practically zero. However, if the angle I, by which the vector differs from the vertical, is considerable, the calculated angle of slope must be reduced by an angle of 90° — I.

A section through the magnetized bodies is illustrated along the ΔT curve, depth and the angle of dip of the middle body being depicted on the assumption that these components of occurrence are identical, in all 3 bodies.

For the second and third ΔT curves, depicted on Figure 37, the depths are calculated in accordance with the gradients near the points of inflection, at altitude h and h+500 m. Along the left branches of the curves we find a depth of occurrence (after subtraction of flight altitude, 100 m), of 900 and 900 m, and on the right arm we obtain 1,070 and 1,170 m. In view of drilling data and information on the topography of the base rocks in the given area, we may consider the results of the calculation to be completed satisfactory. In this connection we must remember that the materials with which we are working are copies of copies and that the ordinates are given on a smaller scale than on the magnetogram. Errors in drawing the curves, particularly in the region of maximum gradient, have a very major effect on the results of the calculations. This makes it necessary to make use of ΔT curves taken directly from magnetograms in the same or larger scales. The normal field may be chosen arbitrarily. Strict corrections for temperature, daily variations, normal gradient, and zero-point creep are not required, as the calculations are based on short segments of route trips, covered by aircraft in only a few minutes.

13. Calculation of Depth and Other Characteristics of Occurrence by Means of the Higher Derivatives

The preceding paragraph shows that the method of calculation of depth in terms of maximum gradients of the curve at 2 levels cannot be used if the thickness of the magnetized body exceeds the depth of occurrence only slightly. In order to reduce the mutual effects of the fields of imaginary strata, we resort to the higher derivatives, to wit, $\overline{\frac{\partial^2 Z}{\partial x \, \partial z}}$ or $\overline{\frac{\partial^2 (\Delta T)}{\partial x \, \partial z}}$.

As in the preceding instance, we shall not seek an analytical expression for the second derivative for bodies marked distribution in depth and any degree of magnetization but shall employ the available expression for the field of those bodies of simple form which may be conceived of as sources of the field depicted by the second derivative.

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We regard the first derivative as a magnitude proportional to the field of 2 imaginary strata taken as sections along the sides of the basic stratum. We regard the second derivative as a magnitude proportional to the field of 2 bodies arising as the result of "subtracting" each of the imaginary strata from the same stratum displaced by a distance Δz (Figure 40). As a result of this "subtraction" we obtain a body of horizontal occurrence, with a section in the form of a parallelogram and 2 bands of reverse polarity, the thickness of which depends upon the angle of dip. The distance between the middles of the bands is Δx. Figures of this type appear on both sides of the real stratum at a distance equal to the thickness of the stratum. The field of the paired bands, given a sufficiently steep angle of dip, may be regarded as the derivative of a higher order, and may be ignored. However the field of a body having a section in the form of a parallelogram may be regarded as that of a cylinder. This is entirely permissible if the value chosen for Δx and z are a fraction of the depth of occurrence. Simplifying the formulation, we may say that if we are given a field Z (or ΔT) over a stratum of considerable extent and distribution in depth, the second derivative of Z (or ΔT) along x and z is proportional to the field of 2 figures sectioned along the corners of the stratum, whereby one of the figures is magnetized in the same fashion as the real stratum and the other in the reverse direction. The shape of the cross section of the figure is not significant if the linear dimensions of the section constitute only a fraction of the depth at which the upper edge is located.

The mutual effects of the fields of 2 cylinders decline sharply, relative to the mutual effects of the fields of the 2 strata, so that the equations developed for cylinders may be applied to the positive and negative branches of the $\frac{\partial^2 Z}{\partial x \, \partial z}$ curve, even in cases in which the thickness of the stratum exceeds the depth of its upper edge by a factor of only 2 or 3. In this case the depth of occurrence of the center of a cylinder, corresponding to the depth of the upper edge of the stratum + 1/2 Δz, is calculated by means of equation (11.10) and the angle of dip of the vector for intensity of magnetization, corresponding to the angle of dip of the stratum, + and angle $90^{\circ} - I$, is calculated on equation (11.12)

The techniques for employing the method with the data of aerial magnetic survey are as follows. In accordance with the data of the ΔT curve, calculated directly from the magnetogram, with retention of the scale of the ordinate, and enlargement of the linear scale to 1:50,000 (or 1:25,000, if the depth of occurrence is expressed in the hundreds of meters), we draw the $\frac{\partial(\Delta T)}{\partial x}$ curve. The gradient is taken at one cm intervals on the drawing and is drawn on a scale not finer than 10 gammas per cm. The curve obtained is proportional to the curve over imaginary strata sectioned along the edges of the stratum. We apply the familiar method of calculating the field at a new elevation differing from the initial elevation by one cm on the scale of the drawing.

In accordance with the initial curve of the gradient and the calculated curve at the new altitude, we plot a curve for the differential, which will be curve $\frac{\partial^2(\Delta T)}{\partial x \partial z}$. In accordance with this scale, $\Delta x = \Delta z = 500$ meters. In the case of an isolated stratum the curve will have clearly defined maxima and minima at points corresponding approximately to projections of the edge points of the section. Should there be many strata, the number of paired maxima and minima will reflect the number of strata. In order to apply equation (11.10) it is necessary to calculate the maximum and minimum curve at a new altitude, for example 500 m (one cm on the drawing) above the level to which the curve for the difference applies. If we limit ourselves to calculation of depth, then, assuming that the maximum and minimum at the new low altitude are displaced along the x axis to a very limited degree, we may calculate the values of the field only at points x corresponding to the position of the maximum and minimum of the difference in the curve. In this manner we derive the data required for application of equation (11.10).

If it also be desired to determine the angle of dip, the value of the field at the new altitude must be calculated at many points, so as to make it possible to plot segments of the curve along which the position of the maximum and minimum would be evident.

Let us use an example to explain the utilization of this method. Figure 41 illustrates the ΔT curves along 2 routes, 6 km apart. The segment contains bore holes, and the core and seismic data have been used to establish the upheaval of the foundation rocks, shown in the drawing by broken isolines.

The midportion of the upper curve, within the bounds shown on the drawing by dashed lines, is presented on Figure 42 in a different scale (the working drawing had a scale of 1:50,000). Along this curve we plotted the $\frac{\partial(\Delta T)}{\partial x}$, the middle, solid curve, which was then recalculated for an altitude 500 m different from that at which the measurements had been taken (the broken curve). The lower segments of the curves depict the difference between the continuous and dashed curves $\frac{\partial(\Delta T)}{\partial x}$, that is, the $\frac{\partial^2(\Delta T)}{\partial x \partial z}$ curves. The ordinates depict in graphic fashion the maxima of the second derivatives at the given level and at an altitude 500 m higher. The calculated values for the depths, reduced by $^1/_2\Delta z = 250$ м, and at a 100 m flight altitude, are shown in Figure 41. Figure 43 shows the results of calculations on the lower curve of Δ T in Figure 41.

It should be noted that when the second derivatives are used the error in graphic depiction of the initial ΔT curves effect the results to an even greater degree than when the first are used. As the starting material is a copy of a 1:200,000 chart, in which the ΔT curves are doubtless different to some degree from the original record on the magnetogram, the examples of calculation adduced must be examined primarily from the viewpoint of the method of calculation and not in terms of practical results, although the latter are in fact satisfactory to an adequate degree. The left side of the upper curve in Figure 41 has not been employed in the calculations because in adjacent trip routes the ΔT curves for this side are entirely different and it is therefore impossible to assume bodies of unchanging shape covering a significant area. The angle of dip of the bodies has not been calculated, as no significant displacement in the maximum of the second derivative at the new altitude has been revealed. This testifies to vertical dip. However the reliability of this conclusion is doubtful in view of the small absolute values of the second derivative.

In Figure 42 our attention is attracted by the symmetrical inflexions of the second derivative (the right side of the drawing). If they are reliable, they reflect the inhomogeneity of the magnetic rocks, to wit, the chief maximum and minimum signify the side boundaries of the magnetic rocks, and the secondary maximum and minimum, the side boundaries of the more magnetic rocks in the central portion of the section. The reliability of the conclusion depends upon the degree to which the infinitesmal changes in the gradient of the ΔT field represent the true state of affairs. This may be established with difficulty on the initial ΔT curve.

This method of calculating depth does not depend on the level of the normal field selected. It is also clear that its use does not require corrections for normal gradient, temperature, daily variations, and zero creep by the existing methods, as the calculations are based on short sections of trip routes 20 - 30 km in length. Measurements on these sections take 6-10 minutes to perform. During this interval changes in field not related to geological structure may be regarded as being proportional to time (except in the case of magnetic storms) and insignificant in magnitude. The linear change in the field by the value of the normal gradient does not affect the results of depth calculations.

14. Determination of Magnetic Intensity and Characterization of Rock Composition Thereby

The previous sections have been devoted to examining the methods of determining the dimensions, shapes, and position in space of magnetized bodies, that is, problems of geometry independent of the composition of the bodies in terms of their substance. Formal methods of resolving geometrical problems do not exhaust the possibilities of magnetic prospecting as a branch of geology. The abstract examination of the shape of magnetized bodies, separate from their content(the composition), is merely an auxiliary means employed at a given stage in the geological interpretation of magnetic charts. The fact is that before standard methods for the solution of geometrical problems are put to work it is necessary to have some concept of the geological structure of the given district, geological information on the particular course along which the work is being conducted, data and conclusions arrived at by other methods of geophysics, experience accumulated in magnetic prospecting under analogous conditions, and to employ these and our knowledge of the intensity of magnetization of rocks.

After the components of occurrence have been calculated the geogetrical decision arrived at is checked both by general data on geological structure and by specific data on the particular district under investigation.

Checking in this manner is essential in the first place because the geometrical task is resolved abstractly, on the assumption of homogeneity of composition of both the intrusive rocks and of those revealing distinctive magnetic properties and on the basis of uniform magnetization.

The purely geometrical solution of the problem cannot be considered in isolation from study of its makeup by substance. In determining the latter, magnetic survey opens the way to description of rocks by magnetic intensity. In the general case the facts accumulated make it possible to classify rocks by this characteristic only into very broad categories, usually described in qualitative terms, highly magnetic, weakly magnetic, and virtually nonmagnetic. The former include the ultrabasic and certain of the basic rocks, while the latter include virtually all sedimentary rocks. The weakly magnetic variety are encountered in virtually all classes of rocks, magmatic, sedimentary, and metamorphic.

The classification of rocks by magnetic force being so indefinite, there is no basis for efforts to determine composition by the strength of the magnetic field.

However facts show that magnetic prospecting is in successful use as a method of finding and determining the contours of rock bodies of specific composition and the projects are planned in accordance with the particular types of rocks to be sought. Thus, depending upon circumstances, one seeks to identify peridotites, granite, etc.

The objectives of magnetic prospecting are even more specific when ores distinguishable by their magnetic properties, magnetite ores in particular, are sought.

The fact that it is possible to pose the problem in this form and to resolve it successfully is explained by the fact that in the first place the data of magnetic survey are not taken in isolation from geological and geophysical data on the area under investigation and in the second that rich experience has been accumulated in the application of magnetic research under various geological conditions for the solution of various problems.

Above we examined a number of instances in which data obtained by magnetic survey were employed to explain geological structure without the use of mathematical analysis by resorting primarily to examination of the composition of rocks and the relative dimensions of rocks of various compositions, reflected on magnetic maps as anomalies of specific force and size (Figures 22-25). For example examination of Figure 22 showed that outcrops of ancient rocks are surrounded by effusives(trap rock) the areas of distribution of which are determined by means of their magnetic fields. This is known from first hand familiarization with the locality. If finds clear expression on the magnetic chart in the form of small anomalies of various intensities. In subsequent work the connection found between magnetic field and geological structure is employed in the geological clarification of anomalies of the same type in adjacent areas.

Let us examine another example. Over a large area where the Z-aeromagnetometer was quiet due to a relatively depressed field a weak magnetic anomaly was found at an altitude of about 400 m. When the altitude of the aircraft was reduced the strength of the anomaly increased markedly. This resulted in work being undertaken on the ground on the assumption that the anomaly was caused by an occurrence of iron ore (Figure 44). The results of the survey at ground level established the fact that the strength and shape of the anomaly did indicate the presence of a body of high magnetite content. Its shape was that of a sheet the top of which was close to the surface. All these conclusions were based on experience, available data on the magnetic intensities of various rocks and ores, and general theoretical conclusions as to the spatial distribution of the fields of magnetized bodies.

The use of analytical methods of calculating the components of occurrence and magnetic intensity confirmed the hypothesis that the body lay close to the surface and the probability that the existence of the anomaly was related to the presence of a body of iron ore. One might think that in the given instance magnetic survey had done all that could be expected of it. However we cannot fail to pay attention to the fact that the iron ore body was discovered in the midst of rocks whose anomalous magnetic fields were practically zero.

This gave no reason to assume that the body was of contact or magnetic origin, as in the former case one would expect to find some change in field during the transition from one type of rock to the next, and in the second case the anomaly would occur over a generally elevated field of varied intensity. The hypothesis which would therefore appear to be best founded is one assuming an occurrence such as iron quartzites, and subsequent drilling bore this out. Determination of magnetic intensity by means of aerial magnetic findings must become a standard precondition of geological interpretation of a magnetic field. Identification of rocks by magnetic evidence, with the development of hypotheses as to the class to which the given rock belongs, is important not only for the case under examination, but also as material for subsequent use.

The data on the magnetic properties of rocks at our disposal have been compiled by isolated measurements of magnetic susceptibility and residual magnetism. Our data on the latter is exceedingly meager.

The accumulation of data on the magnetic intensity of rocks, determined as an average for each body as a whole, offers wider possibilities for identification of rocks by the characteristic in question, based on analysis of magnetic charts employing conclusions derived from other geophysical methods and all available geological data. Calculation of the vector of rock magnetization intensity which in the general case constitutes the geometrical total of the vectors of induced and residual magnetization presents no difficulty if the depth of occurrence, the shape, and the angle of dip of the magnetized body are known. Thus if it is established that the body constitutes a vertical sheet covering a considerable interval of depth the equation adduced in Section 9 above is applicable.

It is easy to derive the formula for calculating I for other simple cases of stratification as well. Specifically, if the depth of occurrence be located by use of the Z (or ΔT) curve, the magnetic intensity I may be calculated in accordance with equation (11.4) in which $b = \Delta x$. When the second derivatives are used, equation (11.3) may be employed in which $M = I\Delta x \ \Delta z\cos\beta$, and the β angle is determined by equation (11.11), while in equation (11.3), the value of $\frac{1}{9}\,tg^2\beta$ may be neglected.

To calculate I it is necessary to know the absolute anomalous intensity of the field. This requires determination of the level of the normal field, the position of which is of no interest in calculating depth of occurrence by investigation of the higher derivatives of potential. Prior calculation of data on the depth and dip of magnetized bodies make it possible to determine the approximate location of this level. The possible errors cannot be very significant, as in case of complications the equation $\int_S ZdS = 0$ serves for purposes of checking.

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CHAPTER III. METHODS IN AERIAL MAGNETOMETRY

15. Accuracy Requirements in Measurements of Magnetic Fields

The methods used in field work and in the subsequent elaboration of aerial magnetometric findings must be in accord with the object of solving the geological problem posed as completely and accurately as possible with minimum expenditure of means and time. The basic questions of method concern the degree of accuracy required, selection of type of instrument, choice of survey routes, elaboration and presentation of the results of the survey, and methods of geological interpretation of the results. They are resolved in accordance with concrete geological problems with allowance for the technical and economic conditions involved. In all cases the accuracy with which the magnetic field is measured must meet the highest standards technically attainable, limited solely by the equipment and considerations of economy. Aerial magnetometers that provide the highest accuracy now attainable are considerably more expensive than other models. Therefore to this day aerial magnetic surveying often employs light Z-magnetometers, relatively inexpensive to use, if the prospecting problems in question have to do with discovery of magnetic anomalies of significant intensity. This would apply, for example, to the search for magnetite occurrences and in prospecting for ores of contact origin in zones of contact between basic and ultrabasic intrusions with ore-bearing rocks.

The data obtained by Z-aeromagnetometric survey which may involve a factor for error of 100 in either direction cannot be used, with rare exceptions, to calculate the dimensions and depths of occurrence of the sources of anomalies. They are used primarily to isolate areas offering worthwhile prospects for further work from the ground and to provide data supplementing available information on the geological structure of the given district in accordance with those changes in magnetic field revealed by topography which are characteristic of rocks of high magnetic intensity. Measurement of the magnetic field to the minimum error possible with the given equipment is a rule to which there are no exceptions. This requirement cannot be relaxed under any conditions, as the more accurate the measurements the higher the accuracy to which the problem is resolved and, further, the greater the possibility of utilization of the data to resolve problems of geological mapping.

The same considerations govern the requirement that surveys with the T-aeromagnetometer be as accurate as possible. Data obtained by aerial magnetic survey with the T-aeromagnetometer are successfully employed not only for general characterization of structural forms but for calculating the depth of occurrence of the sources of anomalies. This is very important in the study of the geological structure of platform regions with thick sedimentary formations. The fact that the results of these calculations are no more than approximate is explainable to a considerable degree by the fact that the methods of calculating depth now applied are valid only for the simplest anomalies, which are relatively rare in actual practice. If the anomalies observed by aerial magnetic survey differ somewhat from the theoretical fields created by bodies of the simplest shapes, the depths are calculated within an error the magnitude of which is only slightly dependent upon variations in the error of measurement permissible with the T-aeromagnetometer. Under these conditions the requirement of minimal errors of measurement does not justify recourse to the laborious processes of surveying by ground teams in terms of the practical value of the improved data obtainable in this manner.

Calculation of the second and third derivatives of the magnetic potential permits use of methods of mathematical analysis to calculate depths not only for the simplest but also for complex magnetic anomalies and simultaneously to obtain significant approximation between the calculated and real depth values. In this case high accuracy of measurement becomes of decisive importance. This is clear from the theory of the method and from the examples adduced above. Therefore the requirement that the highest accuracy attainable with the given type of aeromagnetometer be obtained is most important. In discussing this question it is impossible to leave out of consideration the need for constant perfection of methods of calculating depths and other components of occurrence in accordance with magnetic measurements. New methods are applicable not only to new surveys but also to those previously performed. However the accuracy of the solutions found is always directly related to the accuracy of the starting data. The equipment now in use is capable of providing measurements to an accuracy, as determined by repeated measurements, of $B \pm (60 + 10\%)$ with the Z-aeromagnetometer and of $B \pm (10 + 1\%)$ with the T-aeromagnetometer. Specific accuracy requirements in individual instances are governed by the plan of work and the instructions in effect.

16. Correlating the Measured Values for Intensity of Magnetic Field to the Locality

In aerial magnetic survey, measurement of the magnetic field is conducted at points the positions of which must be determined by the use of 3 coordinates. It has become accepted that the results of the measurements are depicted in a plane formed by the x and y coordinates, the third coordinate being described in the text. It is usually the general characteristic for flight altitude, although in many cases data of high accuracy are available for the z coordinate in the form of radio altimeter and barometric altimeter records. There is no need to demonstrate the importance of quantitative determination of the third coordinate (altitude) particularly in cases in which the data of aerial magnetic survey are employed to calculate depth and the other components of occurrence of magnetized bodies.

The techniques and methods of determining the coordinates of an aircraft in flight are examined in special handbooks. The accuracy with which the location of the aircraft must be coordinated with the locality is specified in the rules. Here we deal with certain problems in the latter field related to specific features of the work which in the author's opinion should be reflected in the instructions in the future.

It is an absolute condition for aerial magnetic survey that the rough maps used be scaled no smaller than the scale of the aerial magnetic survey. This condition is always met if the aerial magnetic survey takes place after aerial photographic mapping has been completed. The requirement in question may be neglected only if the process of survey on a given scale demonstrates the need for a more detailed study of the field on particular routes, which is carried out by means of particularly precise landmarks, and also for large scale aerial survey (scale larger than 1:100,000) over areas for which topographical maps of the required scale are lacking. In prospecting to solve pressing problems of the national economy, the absence of large scale maps (that is, 1:50,000 if the aeromagnetic survey is made on that scale) is not permitted to be an obstacle to the fulfillment of the work, as the main problem is resolution of the question as to the presence or absence of particular resources or areas offering good prospects for further prospecting by ground-level techniques.

In connection with the purpose of aerial magnetic survey, the results of which are made use of in subsequent geological research, the most important consideration is correct navigation by the nearest distinct landmarks, which are later employed by geologists on the spot. In desert areas and over water orientation of the measured field values inevitably has to be either with distant landmarks or with geographical coordinates. It is obvious that subsequent determination of the necessary points on the spot requires that the corresponding technical means of determination be available.

The permissible error of orientation depends upon the concrete geological problems to be solved by means of aeromagnetic survey and is determined by the scale of the survey, which as a rule is coordinated with the scale of the geological studies.

The scale of the aerial magnetic survey is determined by the distance between trip routes. Adhering to the average standards of trip route distance per square kilometer of area, aerial magnetic survey is based on a distance of one km between trip routes for work on the scale of 1:100,000, and 2 km for a scale of 1:200,000, etc.

In addition to this standard of scale, there is the requirement that the measured values of the magnetic field be matched with a specific degree of accuracy to the locale, depicted on a map of the same scale. The instructions of the former Ministry of Geology permit "displacement of curves or of individual anomalies" to a value equal to half the distance between the working routes T-aeromagnetometer surveys (paragraphs 108 and 133). In the graph this corresponds to 5 and 2.5 mm respectively. These requirements require elucidation and deviation from them is by no means always a sufficient reason to discard the field data as the instructions provide.

The procedures for checking and evaluating accuracy of orientation should if at all possible be independent of measurements of the magnetic field (photography, radio direction finding, etc). However, if the conditions of work afford no such possibility and the error in orientation is capable of being determined only by repeated measurements as provided in the instructions to which we have referred, it is necessary to determine more strictly which components of graphic description of the field permit comparison of the repeated measurements for evaluation of the error in orientation.

It is impossible to check orientation by the location of the ΔT isolines on the map of the magnetic field, as this is dependent to a considerably greater degree on the error in measurements and the field gradient and also upon the choice of the normal field, which, strictly speaking, shows different degrees of error on each trip route.. Checking in accordance with maximum Z (or ΔT) is possible, but the isolines of the maximum values employed are usually so wide as hardly to be of value. Narrowly localized anomalies with clearly defined linear axes are adequate for this purpose. In the first place however they are not always present on the map. In the second place sharp peaks may be sheared off, in which case the location of the maximum will depend to some degree on the direction of flight. In view of these factors, fairly low requirements for accuracy of orientation have to be placed upon charts of magnetic field given in isolines. This does not prevent them from serving the practical purposes for which they are designed. The fact is that magnetograms provide the data necessary for calculation of depths and other components of occurrence to utmost accuracy and in most satisfactory fashion with a minimum of preliminary elaboration. Wherever this is possible isoline maps need be used only to clarify those major geological characteristics of the given district that have escaped the attention of the researcher in determining the details of the geographical structure required by the scale of the survey.

Evaluation of error in the coordination of data and locality by means of the map entries for geological contours required by the scale of the survey would be the method best satisfying the practical problems of aerial magnetic survey. However these errors result chiefly from the methods used in geological interpretation of the magnetic field. In view of the fact that to a first approximation the line of division between rock bodies having different magnetic properties is determined by the position of points of inflexion of the $\triangle T$ curves, it must be remembered that it is comparison of the positions of these particular curves that is most important to evaluation of error in location by repetition of measurements. The position of these points is not dependent upon the choice of a "normal" field or in the overwhelming majority of cases upon lag in the recording of field intensity. In choosing the directions and lengths of repeat routes, allowance must be made for the considerations set forth above, and the routes must be planned to go in directions intersecting clearly defined anomalies. As far as the concrete requirements for the accuracy of location are concerned, these must be related not only to the scale of aerial magnetic survey but to the scale of the geological studies of which the aerial magnetic survey is a part. From this point of view the requirements set forth in the instructions are insufficiently rigid in certain respects and too demanding in others.

In the practice of aerial magnetic studies it may happen that particular portions of an area studied within a given scale have to be investigated more accurately in connection with geographical work on a larger scale.

It is clear from the data of surveys performed that when the strike of the rocks is clearly defined it is not necessary for the trip routes to be set more closely together. All that is required is to reduce flight altitude and raise the accuracy of orientation. The totality of all available geophysical and geological data provide grounds for confidence that under the given conditions the problem will be solved in accordance with the scale on which the geological research is being conducted. When this economically profitable variant is used, formal considerations relative to observance of the established relationship between the conventional scale of aerial magnetic survey and the requirements for accuracy of orientation must yield place to demands flowing from the purpose for which the work is being conducted, demands that are more rigid in the given instance.

There are also conditions in which the scale of the aerial magnetic survey is known to be several times larger than the scale of the geological structures that can appear on the basis of aeromagnetic and other geophysical data plus that obtained from widely spaced drill holes. By way of example let us cite the 1:200,000 aerial magnetic survey of Western Siberia, the data of which are employed to determine the strike of large structural forms and to calculate the depth of rocks entering into the composition of the foundation of the platform. The structural chart of the platform basement compiled on all available data, including that of aerial magnetic measurements, is hardly capable of satisfying the requirements of a millionth map (the requirements for which have not been developed as yet).

However the desirability of carrying out the aerial magnetic survey by means of routes at 2-km intervals is confirmed by experience, which demonstrates that only with routes so closely spaced is it possible to select a significant number of simple anomalies for which the depth of the sources of the anomalies may be calculated. With reduction in the scale of the survey these possibilities undergo pronounced reduction. It is obvious that in connection with the development of new methods of calculation of depth the number of points at which depth will be calculated increases several fold, but the geometrical structures will in accordance with the calculated components of occurrence always contain an additional factor of error, depending upon the elaboration of questions of interpretation.

If in the given instance fulfillment of the requirement for accuracy of orientation in relation to the scale of the survey causes no complications in the work, there is no reason for reexamination of these requirements. However, if complications which render the performance of the work more difficult should arise, then in connection with the ultimate geological results of the work it is necessary to envisage the possibility of deviations not reflecting upon the accuracy with which the geological results are depicted.

In this connection it is proper to note that the exceptions to the general rule about a specific connection between scale and error of orientation under examination here testify that the criteria for determination of scale of aerial survey now in use are inadequate. This is true to an even greater degree to many-sided operations at ground level, in which geophysical methods are brought to bear to resolve a geological problem within a given scale, each of the component methods being used to resolve partial problems with a different grid of points of measurement and partial overlap of the areas.

The inadequate reflection of the essence of geological surveys in the concept "scale of aerial magnetic survey" is the most convincing argument for the acceptance of exceptions from the general rule as to the relationship between the scale of the survey and the accuracy of orientation, relative to the geological problems in question.

The method now in widest use is visual orientation of the aircraft by landmarks. Maps drawn on the basis of aerial photography on a larger scale than that on which the aerial magnetic survey is run (or on the same scale, if the survey is on a scale of 1:200,000 or more) provide a good foundation for visual orientation, if readily recognizable landmarks distributed with fair uniformity over the area under survey are available.

A check on the accuracy of visual orientation by local landmarks as given on 1:100,000 maps conducted in the West Siberian lowland by pilot S. K. Vereshchagin, employing photography of the locale, gave the following results.

Error	Number of Instances	%
Not over 100 m	400	78
From 100 to 200 m	74	14
From 200 to 300 m	20	4
Not determined	19	4
	513	100

Included in the indeterminate error group were those cases of check sightings in which it was not possible to determine the location of landmarks on the basis of the photographs.

The method of control adopted is not complete, as the error in orientation in the territory between fixed landmarks remains unclear. However, if the overwhelming majority of the points are in good agreement, there is no serious danger of significant drift off course or sharp change in speed in the intervals between landmarks.

In the given instance the orientation of the routes completely satisfies the scale of the survey, as conversion to graphic form would, as the table shows us, result in a displacement of 78% of the control points by less than one mm and only 4% of the points would reveal a maximum displacement of between 2 and 3 mm.

Present-day radio communications make possible a significant easing and precisioning of navigation. The possibilities inherent therein are now undergoing verification in practice.

Error in determination of altitude has thus far not been given attention by workers in aerial magnetic surveying. With the increase in accuracy of measurement this question takes on major significance, as high accuracy of measurement and orientation in the horizontal plane cannot be used to the full if altitude is given only in approximate form.

The final data usually states the altitude from which the survey was taken either as an average or relative to the airport, points at which the altitude was exceeded also being indicated. Reliable determination of flight altitude above the earth's surface within the boundaries of anomalies attracting our attention as subjects for further geological examination is possible only to within a very rough approximation when values are given in this fashion. This is particularly true in cases of broken terrain. Changes in terrain in an area where the magnetic properties of the rocks are fairly uniform may show up as significant changes in magnetic field, which will be interrupted improperly if the change in true altitude be not taken into consideration. Anomalies due to identical geological formations occurring however at different levels in an area of changing terrain will differ. Calculated depths will be referred back to planes the position of which, relative to the earth's surface, have not been determined with sufficient accuracy. All this testifies to the indubitable necessity of determining altitudes with high accuracy along all points on the route by equipping the aircraft with automatic recording radio and barometer altimeters.

In work with the Z-aeromagnetometer, when the survey data is not used to determine depths, it is sufficient to have periodic altitude recordings on the barometric altimeter.

17. Distances between Flights and Altitude

The scale of aerial magnetic survey, which is determined by the geological problems to be solved, requires that the investigation of the magnetic field and its depiction be conducted at the same level of detail. However the detail which the work is capable of revealing depends upon flight altitude, distance between flights, accuracy of measurement of field intensity, and accuracy of orientation of measured data to the locale. All the foregoing conditions of survey are closely interrelated. Only if each is determined upon in coordination with all the others are we sure of deriving the data required to resolve the geological problem posed.

The distinctness of anomaly boundaries increases with reduction in altitude and in distance between flights, but the cost of the survey per unit area rises approximately in proportion to the coefficient of increase in scale. Consequently the increased costs of surveying on a larger scale must be justified by the advantages that may be extracted from a more detailed aerial magnetic map.

As flight altitude increases so does the breadth of the area covered by each separate trip. The distances between routes may be increased accordingly. Consequently there is an increase in the area of survey provided by each running meter of distance covered. While increase in altitude provides a gain in area covered, we lose in clarity of contour for each anomalous field, due to the diminution in intensity of local fields. It is obvious that accuracy of field measurement is a limiting factor relative to the increase in altitude. The greater the accuracy of measurement, the greater the flight altitude permissible with corresponding increase in distance between flights, and vice versa, all other conditions being equal.

The problems of covering the area completely imposes a specific relationship between altitude and the spacing of flights. However complete coverage of the area is by no means a general requirement, because if overall course of the strata are known, it is perfectly satisfactory to depict the contours of anomalies in terms of interpolation of the field in the spaces between flights.

When aerial magnetic surveying is run in connection with search for oil and gas deposits the scales employed are 1:1,000,000 to 1:200,000. This type of survey has to be the most accurate, and therefore the work is always performed with automatic T-aeromagnetometers.

The major geological problems of the survey are determination of the major directions in which the structure runs, discovery of important tectonic faults and their boundaries, and determination of the depths of occurrence of rocks giving rise to magnetic anomalies, with subsequent employment of the calculated depths to plot structural maps of the foundation of the platform zones.

Surveys run at 5 or 10 km spacings between flights provide data accurate enough to meet the first 2 problems above. The depths of the sources of anomalies are calculated at a small number of points, in view of the very limited possibilities of the methods of calculation now in use. In conjunction with the geological interpretation of the materials of small scale surveying, areas are chosen for larger scale surveying. The purpose here is geological investigation in greater detail and, in particular, more detailed tracing of structural forms and the topography of the basement rocks.

Millionth and half-millionth surveys having the object of finding large geological structures may be run at an altitude of about 1,000 m above ground level, in which the effect of the magnetic field of small forms becomes infinitesmally small and only the magnetic field created by large structures is recorded. However experience shows that the magnetic fields of small geological formations may be used as check points serving to render precise the shape and dimensions of the large structures which it is the purpose of the aerial magnetic survey to reveal. By way of example we adduce on illustration of the magnetic field over one of the large depressions in Western Siberia. The elevated field over the depression is bounded by a sharply varying field over folded structures adjoining the depression on the east and west (Figure 45). In addition reduction in altitude reduces absolute error in calculating the depth of the sources of anomalies, the tops of which are assumed to relate to the depths of the basement rocks. For these reasons, millionth and half-millionth surveys are run at 300-500 m above the locality. The determination of altitude within permissible limits is based on the requirements of safety in flight.

The 1:200,000 surveys for exact determination of structural forms and developing the topography of the basement rocks must be run at the lowest possible altitude, as reduction in altitude diminishes the error in calculation of depths by increasing the intensity of the anomalies and reducing the absolute error in calculations. Assuming that there has been no change in relative error. Over flat country this type of survey is usually run at 100 m altitude.

In prospecting for ore bodies, 1:200,000, 1:100,000, and 1:50,000 scales are the most common. If the bodies being surveyed create strong magnetic anomalies, as is the case with large magnetite occurrences and ore bodies related to contact zones of basic and ultrabasic formations, the Z-aeromagnetometer is employed. However, if weak magnetic fields have to be studied, it is the T-aeromagnetometer that is used.

Survey on the 1:200,000 scale is used for specific identification of large bodies of magnetic ores and primarily to spot areas meriting further work which are then subjected to more detailed study.

The relation of occurrences of specific types to contact zones, fracture zones, intrusive rocks with identifiable magnetic properties, etc facilitate study in the sense that perspective zones may be found along relatively widely spaced routes, while detailed studies are needed over rather small areas.

The zones of contact rocks with varying magnetic properties are readily identified by characteristic changes in magnetic field. Ore formation in the contact zone, accompanied by segregation of ferromagnetic minerals, results in an increase in the intensity of the magnetic field near or on the boundary of the transition from the positive to the negative fields. In connection with the relatively slight dimensions of ore bodies, the magnetic fields of the latter decline rapidly with increase in altitude. This means that it is desirable to conduct the survey at the lowest possible altitude.

When a large number of flights are made across the contact line there is a high probability that some of them will intersect segments enriched by ferromagnetic inclusions. From these findings conclusions may be drawn as to the prospects offered by the contact zone thus discovered and more detailed surveying may be conducted within the boundaries thereof.

Contact zones of intrusions weakly differentiated in their magnetic properties from ore bodies often present considerable practical interest. This is true, for example, of granitic intrusions in nonmagnetic sedimentary or sedimentary and metamorphic strata. In this situation, the zone of contact with the matemorphosed rocks may be discovered either by the changes in field over the metamorphosed rocks in the contact zone, if they are magnetic, or by peculiarities in the field over the ore bodies. In the former case (Figure 24) one may assume relatively small anomalies which are clearly defined at low altitudes but disappear at high altitudes, in other words, anomalies that are definable only in low flights.

In another case (Figure 25) the contour of the large granite intrusion, which is practically nonmagnetic, is identified by the presence of magnetic anomalies or individual bands of strongly metamorphosed rocks intersected by intrusions. In Figure 25 the line of contact is defined with clarity insufficient for it to be depicted with assurance of accuracy but clearly enough for areas to be marked off for detailed study of the contact zone on a larger scale.

Large fracture zones may show varying magnetic characteristics, depending upon the composition and shape of geological bodies therein.

The question as to flight altitude must also be resolved in favor of minimum altitude, as a characteristic sign of a fracture zone is apt to be a confused magnetic field possibly due to small intrusion forms. At high altitude this characteristic sign may disappear and the field will appear no different than the field of adjacent areas.

One of the major objects of survey on the 200,000 scale, in addition to the specific search for occurrences, is determination of the geophysical signs indicating the degree to which individual areas offer prospects for the mounting of more detailed studies. Employing known data on the presence of ore bodies, geological bodies, and individual discoveries on aerial survey on the 200,000 scale, it is necessary to establish those zonal changes in the field with which known ore bodies or those found by survey are connected. Determination of zonal criteria for the prospects inherent in an area creates the conditions for economic planning of further surveys by the methods of aerial magnetic surveying. In many cases general principles are established rather simply, as for example with contact ores in which magmatic rocks are sharply differentiated from the ores by their magnetic properties or when deposits occur in fracture zones characterized by the strong magnetic properties of the intrusions therein or when the objects of investigation are related to strong magnetic intrusions.

However cases are encountered in which industrial findings are noted on the magnetic chart in the form of isolated anomalies observed against the background of a magnetic field lacking any distinctive signs over a very large territory. An example of this is the anomaly over the iron ore resources of the Angara-Ilim district, which shows up in a 1:200,000 survey in the form of sharp negative peaks along isolated flight routes against the background of a quiet field. It is possible that when the accuracy of the measurements is increased it will prove possible to establish a relationship between these ore bodies and specific zones in which good prospects may exist. At present however the prospecting here demands that flights be made only one km apart.

In studies of ore bodies a preliminary 1:200,000 survey is not an absolute requirement under all conditions. It is desirable in areas that have had little geological study where general geophysical signs indicating good prospects are decisive in selecting districts for direct prospecting. Where geological data exist it is not necessary to confirm the prospects of specific large areas by preliminary survey on a relatively small scale. On the contray surveying on the 1:100,000 scale should be performed at once, or 1:50,000 in areas of particular economic importance.

With regard to aerial magnetic survey for mapping purposes, it may be stated that we have not given attention to the completeness with which the space between trips is covered, due to the fact that when flight routes are plotted across the trend of the rocks it appears entirely proper to fill the intervening spaces by interpolation.

When ore bodies are subjected to direct investigation the situation is significantly different in that, for one thing, the occurrences sought may be lost in the spaces between the trip routes and, for another, the trends of the ore bodies are not always strictly in accord with the course of the rocks. Consequently the question arises as to the completeness with which areas between flight routes have been covered. It is obvious that as flight altitude is increased the territory covered by each separate flight increases but the field intensity of each object declines. If the accuracy of the measurements are great, flight altitude may be higher than with limited accuracy. Consequently, if the problem be posed of covering the largest possible area where anomalies of given size are found (and, in actual practice, anomalies of hypothetical area, based on geological and geophysical experience), it becomes necessary to establish the connection between flight altitude and distance between trips at a given accuracy of measurement.

The problem is resolved easily when the parameters of the objects under study, dimensions, shape, and magnetic intensity, are known. However under real conditions the data required for the calculations are always conditioned assumptions, so that corrections must be made on the basis of field data.

Let us examine the problem of altitude and distance between flights as they apply to bodies of various shapes.

(1) The objects of examination is an ore body of indeterminate course, not penetrating to excessive depths, which may be regarded to a first approximation as a sphere.

The vertical component of the magnetic field of the spherical body vertically magnetized is describable in the horizontal plane along a line passing through the epicenter as follows

$$Z = M\frac{2r^2 - x^2}{(r^2+x^2)^{5/2}}, \qquad (17,1)$$

in which M = Iv, meaning that the magnetic moment of the body is equal to the product of the volume and the magnetic intensity; r is the distance from the center of the sphere to the plane of observation, equal to the flight altitude, h, measured from the upper edge of the deposit, plus the radius of the sphere (r = R+h).

In order for such an anomaly to be spotted, at least one route must pass through the zone in which Z values have been measured. Assuming a fixed accuracy of measurement, we determine the minimal value, Z, which will be fixed definitely by aerial survey with the given type of magnetometer. For example, given a knowledge of the mean square error, m, in measurement with the given instrument, let us consider Z>3m in accordance with the familiar rule. Taking M to be a constant, we rewrite (17,1) as follows:

$$(r^2 + x^2)^{5/2} = A\,(2r^2 - x^2), \qquad (17,2)$$

in which

$$A = \frac{M}{Z}$$

Equation (17.2) determines the dependence of r upon x, that is, the flight altitude relative to the interval between routes. By means of this equation we can find x_{max} as it relates to r at a given value of A.

Solving the problem of finding the maximum function by the usual method, we find

$$5(r^2 + x^2)^{3/2}\,(r + xx^1) = 2A\,(2r - xx^1);$$

assuming x' = 0, we obtain

$$5(r^2 + x^2)^{3/2} = 4A,$$
$$\left(\frac{4}{5}\right)^{2/3} r^2 A^{2/3} - x^2 = 0{,}862\,A^{2/3} - x^2. \qquad (17,3)$$

Writing the value of (17.3) in (17.2), we find:

$$0{,}862^{5/2}\,A^{2/3} = 1{,}724\,A^{2/3} - 3x^2,$$
$$x^2 = 0{,}344\,A^{2/3},$$
$$x = 0{,}585\,A^{1/3},$$
$$r = 0{,}720\,A^{1/3}.$$

The geometrical position of the points governing the maximum width of the area covered in accordance with the flight elevation is an inclined straight line segment passing through the center of the sphere with an angular coefficient of about 0.8.

Figure 46 depicts the Z field of the sphere in vertical section, expressed in millioersteds, given $M = 10^{11}$ (that is, R=50 m, I = 0.2). If the measured Z be taken as 5 millioersteds, the maximum area covered will be at an altitude of h = 150 m above ground level, given x = 160 m, if we neglect the depth to the upper edge of the body. Finding this point on the drawing, we readily see that if the flight altitude be varied in either direction the width of the belt covered will decline significantly.

If the measured value of Z be taken as one millioersted, we find accordingly that $x = 270$ м, $r = 335$ м, $h = 285$ м, or in other words in this case the anomaly will be found at flights between 250 and 300 m altitudes along routes 500-600 m apart.

We see from the drawing that if under given conditions we work from an altitude significantly different from the optimum, say, 150 m higher or lower, the probability of missing the anomaly will increase to approximately 20% in both cases. The optimal ratio is determined by the rough formula that the distance between trip routes is twice the flight altitude.

(2) The objects sought are ore bodies of no clearly-defined direction, but covering a considerable depth (columnar deposits).

The equation for the Z curve along a line passing through the epicenter of the deposit is expressed by the equation

$$Z = m\frac{h}{(h^2+x^2)^{3/2}}, \qquad (17,4)$$

in which m = IS, I is magnetic intensity, and S is the top of the body; h is the flight altitude, relative to which we neglect the depth of the top of the deposit.

Considering that Z and m are given, as we did in the previous case, we convert equation (17.4) as follows:

$$Ah = (h^2 + x^2)^{3/2}, \qquad (17,5)$$

in which

$$A = \frac{m}{Z} = \text{const}.$$

From equation (17.5), which establishes the relationship between h and x, we may find x_{max} for any h. However, in view of the complexity of the analytical expression, we shall confine ourselves to an examination of Figure 47, in which the Z field is depicted in the form of isolines in vertical section, given m = 10^6 cgsm (for example, $S = 200\ м^2, I = 0,5$). Let us assume for example that the measured value is $Z = 3$ мэ. We will find that $x_{max} = 360$ м when $h = 270$ м. Consequently at a flight altitude of 270 m the distance between flight paths must be of the order of 700 m, so that the ratio is close to that determined for a spherical deposit.

As concerns deposits of significant elongation the question as to distance between routes may be examined independent of altitude, if it is previously known that the flight paths will be perpendicular to the long axis of the ore body, and the long axis is not shorter than the space between flight paths. However the course of an ore body is not always known in advance even when the predominant course of the rocks distributed across the area under study is known. Let us see what relationship should exist between altitude and spacing between paths to permit complete coverage of the area when the routes are parallel to the long axis.

(3) The occurrence is a vertical sheet of limited thickness but very deep. In this case the equation for the Z curve normal to the long axis will be

$$Z = 2\mu \frac{h}{h^2 + x^2}, \qquad (17,6)$$

in which h is the flight altitude, in comparison with which we may leave out of consideration the depth of occurrence of the upper surface of the deposit.

Assuming μ and Z to be given, and that $\frac{\mu}{Z} = A = \text{const},$ we obtain

$$h^2 + x^2 = 2Ah. \qquad (17,7)$$

Solving the problem to find the maximum, we obtain:

$$h + xx^1 = A,$$
$$x^1 = O,$$
$$h = A.$$

Substituting the value we have found for h in equation (17.7), we obtain

$$x = A,$$

from which we derive

$$h = x = \frac{\mu}{Z},$$

or in other words complete coverage of the area requires that the most economical flight altitude be determined by equation $h = \frac{\mu}{Z}$, and the distance between flight paths is twice the flight altitude.

For example, assuming the thickness of the stratum to be $2b = 10$ м, $I = 0{,}25$ cgsm, we obtain $\mu = 2{,}5 \cdot 10^2$ cgsm. If we assume the measured value of Z to be 5 millioersteds, h will be 500 m, and the distance between flight paths should be $2x = 1000$ м.

(4) The Z field of a vertical stratum of considerable thickness, given very great distribution in depth, is expressed by equation (4.7).

Assuming $\frac{I}{Z} = A$ and solving the problem to find x_{max}, we obtain

$$\frac{1}{2A} = \operatorname{arctg} \frac{2bh}{h^2 + x^2 - b^2} \qquad (17,8)$$

or, as $\frac{1}{2A}$ is small,

$$\frac{1}{2A}=\frac{2bh}{h^2+x^2-b^2},$$
$$4Abh=h^2+x^2-b^2,$$
$$2Ab=h+xx^1,$$
$$h=2Ab=\frac{2bI}{Z}=\frac{\mu}{Z},$$
$$4A^2b^2=x^2-b^2,$$
$$x=b\sqrt{4A^2+1}\approx 2Ab\approx\frac{\mu}{Z},$$

meaning that we obtain results identical with those in the preceding instance.

(5) The Z field of an occurrence of cylindrical form is expressed by equation (4.5), in which h is the depth of occurrence of the center plus the flight altitude, it being assumed that the depth of occurrence of the top of the deposit is negligible compared to flight altitude. In that case we rewrite the equation, assuming $\frac{\mu}{Z}=A$:

$$(h^2+x^2)^2=2A(h^2-x^2). \qquad (17,9)$$

Taking the first derivative to be zero, we obtain

$$h^2+x^2=A;\; x_{max}=\sqrt{A-h^2}.$$

Substituting the value found for x_{max} into (17.9), we find

$$A^2=2A(2h^2-A),$$
$$3A^2=4Ah^2,$$
$$h=0{,}5\sqrt{3A}=0{,}87\sqrt{A},$$
$$x=0{,}5\sqrt{A}.$$

Let us assume, for example, that the radius of a circular section through the cylinder R is 50 m, the magnetic intensity I is 0.2 cgsm, and the measured value of Z is 5 millioersteds. Then:

$$A=\frac{\pi R^2 0{,}2}{5.10^{-3}}=3\cdot 10^5,$$

from which we find that h is 475 m, the flight altitude, h-R is 425 m, and x_{max} is 275 m, or in other words the flight altitude is somewhat greater than half the distance between flight paths.

(6) The Z field of the vertical stratum at its ultimate distribution in depth is expressed by the equation

$$Z = 2\mu\left[\frac{h-l}{(h-l)^2+x^2} - \frac{h+l}{(h+l)^2+x^2}\right],$$

in which μ is 2bI, 2b is the thickness of the stratum and 2 l is the vertical dimension of the stratum.

Taking $\frac{\mu}{Z}$ = A and solving the problem for x_{max}, we obtain

$$x_{max} = \frac{lA}{l+2A},$$

$$h^2 = \frac{l(l+A)(l+3A)}{l+2A}.$$

Considering $A \gg l$, we obtain the ratio between the height at which the survey was taken and the distance between flight paths, identical to that obtained for a cylinder. However, if the value of l and of A is of the same order, the ratio between altitude and distance between flight paths approaches that established for a vertical stratum of considerable distribution in depth (Figure 48).

Theoretical study of the magnetic field of bodies of simple forms leads to the conclusion that in order for the entire area of survey to be covered, the distance between flight paths must be approximately twice the flight altitude, if the anomalies are created by punctuate sources close to the surface of the earth. A more than 2-fold increase in the intervals between flight paths relative to flight altitude creates conditions under which the anomaly may be lost in the interval between paths.

The real objects of prospecting always are of some length. This need only be 200-300 m for it to be possible to allow a considerable increase in the ratio between the factor under examination, that is, the distance between flight paths and the altitude.

If the altitude of flight above the locality be set at 100 m and must not be higher due to the risk of missing the anomaly because of low intensity at significant altitudes, the distance between flight paths, with allowance for the dimension along the trend, may be set at 500 m.

Any further increase in the intervals between flight paths would make it impossible to be sure that the area will be completely mapped, within the requirement that all bodies at least 200-300 m long be spotted.

If experimental work and available geological data provide reason for being confident that at an altitude of 200 m all anomalies of ~~practical~~ interest will still be intense enough to be recorded, it is more desirable to work at this altitude and to increase the intervals between flight paths to 700, 800, or even 1,000 m. This involves the assumption that anomalies of practical significance include only those greater than 500 m in length.

If mineral deposits are long and the flights are transverse to the trend, the interrelationship between flight altitude and distance between flight paths disappears. The distance between routes is determined in accordance with length and the altitude is as low as possible.

The experience of aerial magnetic prospecting for highly magnetized varieties of ore, confirms its practicality, provided that the method of search be rational. There are no standard methods of work applicable to all conditions. The only thing that holds equally for all conditions is the necessity for comparative study of magnetic field and geological map for geophysical signs of ore.

This requires that the work begin at the best known areas, and that known deposits be included, if any such are present. The checking of the planned method against known deposits permits rational solution of the most important problems of approach.

In prospecting other ore occurrences, related either to intrusions of given composition or to contact zones or some other geological environment depicted on the magnetic chart, problems as to distance between flight paths and flight altitude are resolved in analogous manner. Contact zones of large extent will be revealed if the distance between flight paths is considerable, while the intensity and nature of the field are best studied from a reduced altitude. However, should it be necessary to study small intrusions, the shape of which approaches the equiaxial, then in this case as with bodies of iron ore of small extent the need arises to coordinate the distance between flight paths and the flight altitude.

18. Measurement of Magnetic Field from Various Altitudes.

In aeromagnetic work the measurements along different flight paths are often taken at differing altitudes for the purpose of shedding light on the nature of the various anomalies by the gradients of their fields and to assist in calculating the depths and dimensions of the objects giving rise to the magnetic anomalies.

Measurement of the Z field above and below the initial level, with the purpose of evaluating the field gradient, may be justified if the Z magnetometer be employed, as the accuracy of the measurements is not high enough to make possible employment of methods of calculation. As far as measurements made with the T-aeromagnetometer are concerned, further measurement of the field from altitude that is only slightly higher is of no greater practical significance than is the determination of the values for the field at the given altitude by calculation. It must be remembered that the values of the field measured at various altitudes must be closely matched to all 3 coordinates, a condition that is not always met by any means. In this situation calculated values for the new altitude determined by calculation are definitely of greater advantage.

Measurement of the field at a higher altitude may be of practical significance in the solution of special problems, for example, experimental determination of the normal gradient along the vertical. It may also be useful in certain special cases, when calculation is impossible for some reason. This would be true, for example, in an effort to calculate a field at a very high altitude for an area near the edge of the zone surveyed.

Should it be necessary to study the field in a plane lower than that at which the survey has been taken, it is necessary under all conditions to give preference to measured and not to calculated values, as the latter involve considerable factors of error.

The undesirability of measuring the magnetic field at various altitudes is further supported by the fact that measurements taken by field expeditions at more than one altitude find no practical application in the majority of cases, although certain useful conclusions may be drawn. By way of example let us employ the ΔT curve measured at 4 altitudes (Figure 49). An examination of these curves shows that they do not fully correspond with each other, a circumstance that may be due either to errors in measurement in the field or in the fact that the routes may have crossed, which would represent a crude error in plotting the routes. The normal field also shows errors. Specifically, it is considerably stronger taken from the highest altitude than it is taken from the lower. It is obvious that this data is unsatisfactory for purposes of exact calculation of components of occurrence. Nevertheless it is possible to draw certain approximated conclusions.

Without giving detailed attention to the general geological interpretation of the field under examination, for which it would be essential to employ a map and not merely a cross-section, in addition to the magnetic field and all the other available geological and geophysical data, let us note only that the given cross-section clearly reveals the boundaries of at least 3 types of rocks (in the broad sense) significantly different in composition. On the right there are rocks that are virtually nonmagnetic and homogeneous in composition. On the left there are rocks whose magnetic intensity is of the order of $50 \cdot 10^{-5}$ cgsm and which are homogeneous in composition. The rocks in the middle show strongly varying magnetic properties and as to the nature of which we shall atempt to offer certain hypotheses on the basis of the measurements at the various levels.

The shape of the intensive anomalies at the lower level justifies the hypothesis that vertical strata of relatively slight thickness are present. In this case $Z_{max} = 2M\frac{1}{h_1 h_2}$, in which M is the magnetic moment of the section, and h_1 and h_2 are the depths of the top and bottom of the stratum. We are now in a position to write 4 equations for the 4 altitudes at which the survey was taken, with 3 unknowns. Correcting the inaccuracies in the curves noted above in relation to the level of the normal field, and measuring the magnetic field of the strata on the left from the maximum values of $\triangle T$, we obtain the following values for $\triangle T_{max}$: 3,800, 2,000, 800, and 360 γ. Employing the 3 lower levels, we find the depth relative to the lower flight altitude: $h_1 = 220$ m and $h_2 = 8,800$ m. The solution thus found satisfies the value of $\triangle T_{max}$ at the upper level. Now let us proceed to the next large maximum with its values for 3 levels: 1,400, 460, and 180 γ. By the same procedure we find the depths, h_1 being 105 m and h_2 2,600 m. The values of h_1 found for the 2 separate anomalies may be regarded as being very similar, as elimination of the faults in the curves may give rise to errors affecting the results of the calculations for h_1 and h_2. For this reason and also because of the general similarity of the anomalies, the geological causes may be considered to be identical. Judging by the intensity of the field near the upper edge of the bodies, as found by extrapolation, we come to the conclusion that this anomaly may be caused by rocks with high magnetite content.

The fact that the first anomaly is in the vicinity of a contact zone leads to the thought that there may have been contact metamorphosis of the rocks accompanied by the formation of a magnetite deposit. But from this it follows that it is also necessary to explain the other anomaly, 12 km from the first, on the hypothesis that contact phenomena are observable almost uninterruptedly (basing ourselves on the low maxima) over a distance of more than 10 km in a direction perpendicular to the long axis (assuming that the survey has been taken normal thereto). This hypothesis is so improbable that the first presumption, to the effect that the anomaly is related to an iron ore occurrence of contact origin, must be abandoned, and another more probable supposition made instead. This latter is that the entire central field of the anomaly represents metamorphic shales through which there are scattered rocks of high magnetite content.

Investigation of this hypothesis will involve the use of maps of the magnetic field, and all available geological and geophysical data on the area.

Both the example cited and other data on measurements at various levels lead to the conclusion that measurements made at different altitudes for the purpose of determining the depth of occurrence and the dimensions of bodies must satisfy considerably stricter requirements as to accuracy of measurement and orientation. Special attention must be given to accurate plotting of the flight routes in a uniform vertical plane, with strict adherence to flight altitude. The difficulty encountered in adhering to these conditions presents convincing proof that it is simpler, quicker, and cheaper to get this data for calculation of depth by calculating the field at various altitudes by the data obtained for that on the lowest altitude. In cases where practical considerations do require measurement of the field at a new altitude, orientation must be as exact as possible along all 3 coordinates, with no deviation in flight path from a single vertical plane.

In the absence of clear landmarks along the route, one must either dispense with surveying along the route selected or set out signals on the ground for purposes of visual orientation.

All measurements at each elevation must be made in the course of a single flight, and under the most favorable possible meteorological conditions. However each such series must be taken twice at the respective altitudes and the measurements must terminate at the altitude at which they were begun. Fulfillment of these requirements assures minimum error due to the choice of a "normal" field, and to zero creep, as well as close adherence of the flight path to the locale, and accurate determination of flight altitude.

In work with the T aeromagnetometer it is necessary to measure the temperature inside the cabin with a sensitive element so as to make the proper corrections, as change in altitude invariably carries with it change in temperature. In addition the ΔT measurement must be corrected for the normal vertical gradient, which has to be determined experimentally on a segment with a normal field. If magnetic disturbances be noted in measurements at any altitude, the measurements must be repeated.

In determining the number of different elevations, one must be guided by consideration of the manner in which it is proposed to make use of the data obtained. In other words the methods of resolving the problem should be worked out in advance.

In choosing the intervals the areal distribution of the anomaly is decisive. For example, if an anomaly observed at 100-200 m does not exceed one km in width, there is no purpose in taking further measurements at one km altitude. It would evidently be sufficient to change the altitude by 200-300 m. But when anomalies are very large, running to tens of kilometers in width, a change of only 200-300 m in altitude would add virtually nothing new. In such a case one should fly at the ceiling of the aircraft. The taking of measurements at a number of altitudes without clearly defined purpose and methods of solving the problems posed, is undesirable. Only if the manner in which the data to be obtained will be employed has been worked out in advance will questions as to choice of directions, altitudes, methods of orientation, etc be answered in such fashion as to guarantee the most satisfactory results. It goes without saying that the taking of measurements at higher altitudes is decided upon only if experimentally determined data may be expected to offer significant advantages over calculated data.

19. Special Features of Aerial Magnetic Survey in Mountain Areas

In mountainous areas flight altitude relative to the surface of the earth necessarily varies, the amplitude of the variation being dependent upon topography.

Efforts to hold to approximately a single flight elevation over broken country by plotting routes parallel to ridges and valleys have not given positive results, nor could they. An insignificant advantage in determination of slip is purchased at the expense of complications due to the need to obtain large overlaps, and violation of one of the most important conditions of aeromagnetic survey, that the flight paths be perpendicular to the course of the strata.

The experience acquired in work under mountain conditions leads to the conclusion that when surveying is onaa scale of 1:200,000 and larger it is necessary to hold to the minimal elevation permissible in terms of the instructions and flying conditions. If the relative altitude is high, large areas will prove to have been recorded at greater altitudes than are desired for work at the given scale. In order to hold to a minimum areas taken from very high altitudes it is necessary to consider the possibility of dividing the entire region subject to survey into sections large enough to make it worthwhile to do each at a given altitude above sea level, with some diminution in true flight altitude. This is quite within the realm of possibility in the case of work in the foothills and mountains of a single folded region.

For surveys on a smaller scale, pursuing the object of discovering large geological structures, the altitude at which the survey is taken may be increased, depending upon the conditions posed by the problem.

Under conditions in which the survey is run at various levels, that is, when the various sections are taken at differing absolute altitudes due to considerations of topography, partial overlapping of the entire geological region must be provided for at low altitude so as to derive data for determining the effect of altitude on the general nature of the field.

If the area presents a gradual elevation and if circumstances require flight altitude to be minimal, it is entirely proper to make the survey along an inclined plane which approximately follows the surface slope. The apparent difficulty presented by the fact that a survey taken in this manner cannot be measured against a specific altitude above sea level is actually not significant, because determination of altitude has to be subject to resolution of the geological problems, if the latter are best solved at low altitude, even survey along a wave-like path is not to be rejected, if no obstacles appear in terms of flying and the normal functioning of the equipment.

Under all conditions of surveying in mountain areas, determination of slip is of exceptional importance. The use of radio altimeters recording automatically in the course of the high accuracy survey is an absolute necessity. When the survey is from light aircraft not carrying this equipment, both the pilot and the magnetologist must record directly on the tape the moment at which a ridge or valley is crossed.

When the results of the survey are depicted in the form of curves along the flight course it is essential that the findings be matched to the topography, as experience has shown that if magnetic rocks are distributed through districts with sharply changing topography the curve of the magnetic field is highly dependent upon the relief.

20. Control Measurements

Changes in the ordinates of the curves recorded on the magnetogram are governed not only by changes in the intensity of the magnetic field created by geological bodies, but also by many other causes, the effects of which must be eliminated to the greatest possible degree.

One of the most important types of interference seriously affecting changes in the ordinates of the Z and ΔT curves is due to unstable functioning of the equipment comprised in the aeromagnetometer set. Anomalies appearing due to this error in measurement are called "zero creep" and manifest themselves in the fact that with the passage of time and no change in the external magnetic field the base (or zero) point on the magnetogram fails to remain constant. Zero creep varies from one set of equipment to the next. It fluctuates approximately in the range of 10 to 50γ per hour.

The most general method of determining zero creep consists of repeating the measurement after the lapse of a specific period of time. When magnetic survey is taken from ground level, control and base points are used to check the zero point. In aerial magnetic surveying, analogously, determination of the zero line is made along a check route, and there may also be measurements along the base routes. Differences in the ordinates of the curves during the first and second measurements, corrected for the effect of temperature and daily variation, is regarded as zero creep due to unexplained causes and is taken by convention to be proportional to the time factor. The smaller the interval between the first and second observation, the closer to truth is the assumed linear zero creep proportional to the time factor. The maximum interval between 2 successive control measurements is the duration of one flight. In this case the first control route measurement is made before taking off on the working trips and the second after the work along the given route has been completed.

When a Z aeromagnetometer is employed the major cause for displacement of the zero line once the instrument has settled down is change in the magnetic field compensating the Z_0 field in the region of rotation of the coil (the qualification about the instrument having settled down is made because during the first 10-20 minutes of operation the displacement of the zero point may be considerable, due to a number of other considerations stated in the technical instructions for operation of the equipment). As we know, in the first models of the coil aeromagnetometer a large portion of the initial field Z_0 was suppressed by the field of the permanent magnets and 10-20% by the field of the current passing through the windings of the fine and crude compensation coils. A change in the latter compensates for change in the field along the routes. A decline in the voltage of the batteries feeding the compensation coils and change in the magnetic moment of the compensating magnet are the major causes of systematic creep in the zero point.

In the 1946 model the influence of these sources was reduced because the fields of fine and crude compensation were arranged in opposite direction, given $Z = Z_0$. In this situation displacement of the zero line is affected by lack of constancy in the battery voltage only if a difference arises in the fields of fine and crude compensation. In the 1950 and 1951 models the displacement of the

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zero line in accordance with change in the voltage of the compensation battery is eliminated almost completely, as the initial field is suppressed by the field of the magnet without residue, and when the coil fields are employed for compensation anomalous voltages in the power supply are controlled and corrected by matching against the voltage of the standard element.

Thus the one compensation field remaining uncontrolled is that of the magnet, which changes noticeably with change in temperature. Change in temperature also causes change in the relative positions of the magnet and the induction coil, the resistance of the electrical circuits, and the battery voltage (including the standard element). As the instrument is not insulated against heat and has no special equipment to suppress or reduce the effects of temperature, it must be assumed that the shift in the zero line in the most recent instruments depends chiefly upon temperature.

Aeromagnetic survey is run either early in the morning or late at night. A flight is usually of 4 hours duration. Under these conditions it may be assumed that the change in direction from the beginning to the end of the flight will be in one direction only and consequently the displacement of the zero line for the reason indicated will also be only in one direction.

There is no doubt of the fact that fluctuations in generator voltage feeding the motor of the induction frame affects the position of the zero line. The use of a resistanse box will stabilize this voltage considerably, but certain voltage variations will occur nonetheless. When a wind-power generator is employed the voltage variations at the motor terminals are not a function of time. However, if batteries are used, the voltage will drop with the passage of time.

Limiting ourselves here to an examination of the major causes of displacement in the zero line of the Z aeromagnetometer, we must conclude that regular zero creep during the flight should be in one direction only and, dependent upon the properties of the power source, the creep may be taken to within a satisfactory degree of accuracy to be proportional to time where brief periods are concerned.

Flights with the T aeromagnetometer are usually 8 hours in duration. With flights of this duration and with the considerably stricter requirements of accuracy it is not possible to work on the assumption that the shift in the zero point is linear.

The fact is that tests of zero shift during the shorter intervals show that with certain models the hypothesis that the displacement is linear is not valid even for purposes of very rough approximation. This raises the question of assuring control of the readings on the instrument for briefer periods within the interval between measurements on check trips.

In selecting the check route for regular monitoring of the zero point it is necessary to be guided not only by technical but also by economic considerations. Consideration of both leads to the establishment of the following requirements.

(1) For convenience and economy of available summer time the check route must be near the airport and have distinct boundary and intermediate landmarks.

(2) The check route must be in a quiet magnetic field to eliminate the effect of inaccurate plotting of the check route in altitude and in the horizontal plane. The measurements are run at

the same altitude as the survey proper. Should it prove impossible to locate a route near the airfield to meet these requirements, the check route may be laid out in an anomalous field. In this case however the measurements must be run at high altitude to reduce the relative effect of anomalies should the check route be flown inaccurately either in altitude or in the horizontal plane. Local conditions determine whether it is more economical to set the check route at some distance from the airfield, at low altitude, or alongside it, at high altitude.

(3) The check route is set at a length necessary and sufficient to record the magnetic field with due confidence and to check the functioning of the instrument. In practice this requires a flight of about 10 km for a PO-2 aircraft and about 25-30 km for an LI-2 with T aeromagnetometer.

(4) When working with an aerial magnetometer installed within the aircraft the course of the check route is set parallel to that of the actual routes to preserve unchanged the inductive effect of the geomagnetic field on the masses of iron around the magnetometer. If the deviation of the zero values on the outbound and inbound flights exceed the permissible levels, due to differences in induction, measurement on the control route must always be taken in each direction.

(5) Measurements on the control route are always made before and after the actual survey flights have been flown.

Should 2 or more airstrips be used within the limits of the area under study, new check routes are laid out near each strip, each such route being carefully oriented relative to the preceding one. The control routes must be entered on the map and described in the report, with indication as to the anomalous field on each control route if it should differ from the normal. This is necessary for purposes of aligning the survey with those on adjacent areas. Alignment of the new control route with the old for the purpose of determining the difference in the values of the fields along the old and new control routes may be performed simultaneous with the plotting of control secants of the routes.

Significant errors in determining the zero creep in operating with the T aeromagnetometer, due to an inaccurate hypothesis being made as to the linearity of the zero creep, results in the appearance of systematic error in the ordinates of the ΔT curves, which changes rather slowly with progress along the route. This error is not sufficient to affect seriously the geological conclusions on each anomaly taken separately, as it takes no more than a few minutes to traverse even the largest anomaly. The effect of these errors is felt only in compiling charts of the magnetic field of large areas, maps to be used for the derivation of general judgments and conclusions as to the geological structure of the area under study, and therefore governing the planning of small scale geological survey. Thus the larger the scale of the aerial magnetic survey, the less the practical significance of the systematic error to which we have reference. In small scale survey the significance of systematic error rises and measures must be taken to eliminate it or reduce it sharply.

One of the methods used for obtaining a more precise picture of zero creep is the taking of a repeated series of measurements over a short stretch of the order of 20 km at the beginning of the n+1 route after completion of the n+2 and before setting out on the n+3. These repeated measurements are spaced to occur every 2-2.5 hours. The deviation of the average values of the ordinates along a section of a given route during the first and second measurements of ΔT governs the zero creep during a given time interval. In some cases zero creep may be determined very strictly, as described below, for the purpose of setting up base lines. In the area to be surveyed routes are plotted virtually perpendicular to the projected working routes and along clearly-distinguished landmarks.

Test routes should preferably pass through the starting and/or finish points of the planned working routes. If the length of the latter is such as to be traversable by the aircraft in less than 2 hours 2 base lines at the boundaries of the section are sufficient. Where more accurate results are desired or where the length of the working routes takes more than 2 hours to cover it is important that there be a third base line passing approximately through the midpoint of the working routes.

Measurements for the base routes are run at the same altitude as the survey of the route. At each such altitude measurements are taken at least twice, the number of times depending upon whether the disagreement in the values of the Z or ΔT fields exceeds the permissible level. The effects of variations, temperature, and zero creep are eliminated and the measured values are reduced to the values of the field on the check route, which are tentatively taken as normal.

Where there are such baseline routes with good landmarks at the beginning and end of each trip route (along with points of intersection with the intermediate route if such a route has been laid down) the working routes do not have to be oriented to the check routes and the latter are used only to tune up the T aeromagnetometer. The processing of the curves will consist in lining up the ordinates of the curves at the points where the working routes intersect the base lines. The further elaboration of the data to compile a map of the magnetic field will consist of eliminating the normal gradient and the remainder of the normal field.

If there are adequate data for obtaining the gradient of the normal field from the measurements on the base routes this is what is to be done. Then the curves for the working routes, correlated at their termini to the values for the fields on the base routes, will be freed of the influence of the normal gradient. Use of this method is possible only when there are good landmarks on the base routes for each working route. In nature these conditions are met only under exceptional conditions. Consequently there is no basis for assuming that this method will be widely employed.

Zero creep is the main source of error. In work with the Z aeromagnetometer the effect of temperature and daily variations is not examined independently but enters into the total "zero creep" error. In work with the A aeromagnetometer changes in the readings due to change in temperature and daily variations must be considered separately if the intervals between check observations are larger than about 2 hours. In the high latitudes the allowance for variation must always be conducted independently of the time intervals between check measurements. When survey covers a wide band of changing altitudes or takes place during days with sharp temperature variation, corrections must be made even when the time intervals between check measurements are short.

Variations in δT are calculated on a formula developed from the equation $T^2 = Z^2 + H^2$, to wit:

$$\delta T = \delta Z \sin I + \delta H \cos I,$$

where δZ and δH are variations in the vertical and horizontal components, and I is the angle of dip.

Thus each expedition must have Z and H variometers to measure these variations.

Let it be noted that an instrument for direct measurement of δT may easily be designed on the principle of the balance. All that is needed is to set up a magnetic system in the plane of the magnetic meridian so that the magnetic plates are perpendicular to the total T vector. In order to adjust the system for the magnetic meridian of the given locality the magnetic plates must have an attachment for measuring the angle of dip of their magnetic axis relative to the horizon. The presence of such an instrument very greatly simplifies the complex work of calculators when they use the records of 2 variometers.

In order to evaluate the error in measurement and orientation measurements are repeated along the routes previously traversed, intersecting anomalies of average intensity and gradient. With this object, series of flight routes are plotted approximately normal to the workingg route, primarily to make possible subsequent lining up of the normal field as maps of the magnetic field are plotted.

There is no point to covering much mileage on repeated and secant routes, as these measurements do not improve the accuracy of the work but only serve to evaluate it. If an expedition devotes 10% of the total survey flight mileage to this, then, assuming the total cost to be one million rubles, this factor will come to 100,000. It is difficult to justify such an expense if the check measurements for determination of quality find no reflection in the geological conclusions, as is virtually always the case in actual practice. A small number of routes must be chosen for purposes of repeat measurements, but those selected must be the most typical for the purposes of solving the geological problems posed by changes in field. However survey along secant routes should be done by using the flights from the airfield to the point at which work is to be undertaken. The mileage needed to determine the accuracy of the work and for purposes of alignment should be 5% of the total or less.

21. Elaboration of Magnetograms for Calculation of Depths and Other Components of Occurrence of Magnetized Bodies

The greatest possible accuracy of measurement of the magnetic field is the most important single consideration in the data employed to calculate depth of occurrence, dimensions, and the angle of dip of magnetized bodies. Every operation involving the curves directly recorded on the magnetogram, simple hand copying, change of scale, introduction of corrections with redrafting of the curves, etc, is a source of additional error. For this reason the calculation of the depths and the other components of occurrence demand employment of ΔT curves that have been reworked only to the minimum degree necessary for calculation.

The only operation absolutely essential is the transfer of the ΔT curves to millimeter-square graph paper, in a linear scale of not less than 1:50,000, the scale of the ordinate being retained. If the linear scale of entry on the magnetogram is determined by a winding rate of 8 m per hour the curve will be drawn on a scale of 1:25,000.

We know that in work with the T aeromagnetometer a constant scale is employed for the ordinate (1,000 γ for the entire width of the 28 cm tape), and one of 3 scales for recording the route traversed: 1,2, and 8 m per hour. At an average rate of 200 km per hour this

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corresponds to scales of 1:200,000, 1:100,000, and 1:25,000. The field is always recorded on a larger scale than that of the survey. It is desirable that, regardless of the scale of the survey, the scale of the record be not less than 1:100,000. In other words, the rate at which the tape winds should be 2 and 8 m per hour, the former being used only for survey at very high altitude, where there is no possibility of encountering fields with high gradients.

The following rules must be adhered to as the ΔT curve is transferred to millimeter paper.

(a) The nonuniform scale for the route traversed, varying in accordance with the ground speed of the aircraft, must be rendered uniform, the new scale being not smaller than 1:50,000.

(b) The ΔT ordinates beyond the first thousand gammas on the tape, must be totalled.

(c) The ΔT ordinates must be counted not from a horizontal straight line segment but from a sloping line drawn to correspond approximately to the overall increase or decrease in the ordinates of the curves on segments of approximately 50 km.

No strict correction for zero creep, temperature, variations, and normal gradient are required, at this stage of the work, as depths may be calculated adequately by means of anomalies of limited width, not exceeding 20-30 km. Over this distance, which is covered by an aircraft in a few minutes, the total of all the corrections may be regarded as being a linear function of the distance (except where magnetic storms are concerned). A small error in the angle of dip of the zero line may well be present but it is of no practical value in calculating depths. The choice of the level of the field conventionally regarded as normal is also of no significance. In cases where methods of depth calculation related to determination of the level of the normal field are employed, it will be necessary to proceed in the same manner as is now the case in employing maps of the magnetic field, to wit, a level is selected for each individual anomaly, often by the particular worker's intuition.

Without undertaking a critique of this method, we note merely that these methods of calculating depth are applicable only to a very limited number of anomalies. As far as most anomalies are concerned, including those just noted, it is necessary to employ methods of calculating depths, dimensions of outcrops, and angle of dip, unrelated to the depth of the normal field.

The selection of a normal field, founded on real considerations, is justified only when the number of geological problems includes the problem of calculating the depth of occurrence of the bottom of the magnetised body and calculation of the intensity of the magnetized rocks.

When ΔT curves are depicted on the millimeter graph, they should be superimposed, with adherence to the accepted scale along the direction of the routes and to a larger scale in the direction perpendicular thereto. The scale for the intervals between routes is chosen so that the ΔT curves will not intersect and so that space will remain for the drawing of the subsidiary curves. It is unnecessary for curves covering the entire course of the route to be depicted on a single sheet. The entire area covered may be divided into a number of segments, each convenient to work with, and the surves entered thereon, maintaining an overlap of 10-15 cm. If the border happens to be at an anomaly the overlap may be larger.

A topographic profile is drawn beneath each ΔT curve, as is the flight path, as read from the radio and barometric altimeters, and, for purposes of checking, a profile from the topographic map. The work sheets thus compiled must be examined for accuracy of field measurements and orientation before being employed to calculate the depths of occurrence of sources of the anomalies.

The methods of aerial magnetic survey make possible a general preliminary evaluation of the accuracy of the measurements and orientation by an examination of the results of the measurements as set forth in the graphic form prescribed. True, the survey is conducted by solidly covering large areas with parallel trip routes, the distances between which will as a rule be smaller than those of the bodies to be identified and mapped. Consequently we may expect to find an interrelation between the magnetic field intensities of a series of adjacent trip routes. This relationship is seen in its sharpest form in repetition of anomalies from route to route, with gradual change in the shape and amplitude of the curves, repetition of stepwise change in field intensity, and in the fact that it is possible to follow a uniform field on many routes. Taken together all this makes it possible to follow the axis of extended anomalies, the contours of large regional changes in field, and the contours of homogeneous fields.

By following changes in field along the trip routes and from one route to the next it becomes possible to identify the pattern of appearance of extreme values, thus eliminating doubts as to their reality. On the other hand the appearance of marked changes in field on one trip route only, changes not suggested by the general character of the changes in the field on adjacent routes and in the given district in general, and not such as would seem to be a result of the known geological structure of the area, gives rise to doubt. This does not mean that isolated anomalies are inevitably false. We know of geological regions in which sharply defined and narrowly localized peaks of positive and negative values are typical, as may be seen from the magnetic chart of a specific district (Figure 20). Dubious changes in field are eliminated from examination hereafter in our calculations of depth of occurrence. However, if isolated anomalies should come to light in connection with the solution of geological problems (for example, in efforts to find highly magnetized ores), they must be confirmed by repeated flights.

Quantitative estimates of errors in measurement are based on the results of repeated measurements over individual routes laid out along clearly defined landmarks.

The ΔT curves of repeated measurements are calculated in the same fashion as those for all working routes. The greatest significance in calculating depth and other components of occurrence attaches to evaluation of the accuracy of relative changes in field, within the bounds of each individual anomaly employed in the calculations. Therefore in order to evaluate the error in measurements it is important to rule out the effect of all systematic errors such as those related to orientation, zero creep due to various causes, and errors in determination of the normal field.

This being the case, we shift all the curves to an identical altitude before proceeding to compare them, by recalculation for higher altitudes at points where differences have been found. Next we superpose the curves not by the common coordinate points but by the characteristic points of coincidence on the ΔT curves, which may include clearly defined maxima and minima and their gradients (points of inflection, that is). As the level of the normal field has been set arbitrarily, displacement of the curves along the vertical and adjustment of the angle of dip of the conventional zero line are entirely permissible. Where long trip routes are concerned it is entirely possible that after the superposition of the coordinates of the characteristic extreme points the curves will show a regular divergence both along the trip routes and the slope of the conventional zero line. As the object in the given instance is not a general evaluation of the accuracy of the future map of the magnetic field but of the accuracy of the relative changes in field of individual anomalies, discovery of systematic divergence of the curves requires that they be compared along individual segments of the route, with superposition of the characteristic extreme points bounding the various segments. Naturally the segments cannot be smaller than the width of the anomalous zones being used at the same time for depth calculations.

On each separate segment, after the superposition of the characteristic points, the differences in the ordinates are calculated at intervals of 0.5-1.0 km. The sum of all the differences should be close to zero. If it differs from zero to any considerable degree this means that a systematic error has occurred which has to be eliminated by repeating the superposition of the curves and calculation of the $\delta(\Delta T)$ differences. After differences have been found to satisfy the condition that $\Sigma\, \delta\, (\Delta T) = 0$, the mean square error is found on the formula

$$m = \pm \sqrt{\frac{\Sigma[\delta(\Delta T)]^2}{2n}},$$

in which n is the number of points employed.

Figure 50 depicts the ΔT curves twice measured on a single trip. It is clear that in order to eliminate errors in orientation and evaluation of the accuracy of measurement it is necessary to shift

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the right side until it coincides with the ΔT maxima, while the left side is permitted to remain where it is.

The error in orienting the points on the route is determined by applying the ΔT curves adjusted to a single altitude to coordinate points, subsequent to which the differences in the coordinates of the characteristic points are derived. In the given case the problem is the calculation not of the accidental error in the position of each point on the curve but the systematic errors in orientation of large segments, due in particular to the consequences of accidental errors in orienting the aircraft to specific landmarks.

In order to determine the specific error in orientation the equation adduced above will not do. The error in orientation is calculated as the arithmetic mean of all errors found in the position of the characteristic points on the ΔT curve. However it is impossible to use the average of the entire lengthy route, as errors on specific segments may differ in value with the result that the error may remain at zero. Therefore it is calculated separately for the various sectors characterized by distinctly different and systematic divergences. If there are sudden changes they may be found to coincide with the landmarks used for orientation.

Calculations of this order are run for all the routes on which repeat measurement have been made. Only after the mean errors on the individual sectors have been calculated is it possible to apply the formula adduced above specifically to mean errors. The magnitude calculated will characterize the mean square accidental error in orienting the aircraft to the landmarks employed. If the number of repeat routes is small the data obtained will be inadequate to calculate the mean square error, in which case the error is characterized by the largest actual displacement.

The calculated mean square error in measurement of the ΔT field determines the approximate limits of the possible errors in relative ΔT values. In accordance with the familiar rules for distribution of error the probability of triple error is 0.3%, meaning that if $m = \pm 10\ \gamma$, the possible errors may attain 30γ. Direct employment of the calculated error for quantitative evaluation of the error resultant therefrom in calculation of depth and other components is not possible.

In addition the calculated error does not resolve the problem as to whether certain weak anomalies, whose amplitude is within the limits of error, actually exist. To do this it is necessary to know the error in recording the gradient of the field in the direction of the trip route, which, given a constant factor of error m, is largely dependent upon the amplitude of fluctuation in the ΔT field. Therefore it cannot be asserted beforehand that geometrical plottings (depth, dimensions, and dip of magnetized bodies) along the ΔT curve, measured along a section of a given trip route with an error of $m = \pm 5\gamma$, will be more accurate than those plotted along the ΔT curve along some other trip route, where the error is $m = \pm 10\ \gamma$ on the condition that in both cases we are dealing, for example, with anomalies over bodies of very simple form. However it may be stated that in both cases the geometrical structures will be more exact is the error in each will be, for example, only half as great.

Evaluation of the error in the recording of the curves along the route is necessary nevertheless as a measure of the reliability of changes in field along particular sectors designated for calculation of depth and other components of occurrence, even though it cannot be converted into a conrete measure of the error in calculating the components of occurrence.

No difficulty is encountered in calculating the error in measurement of the field gradient by plotting the $\frac{\partial(\Delta T)}{\partial x}$ along 2 ΔT curves, twice measured on a specific route. However a more evident measure of the quality of the ΔT measurement is presented by comparison of sections describing the geometry of magnetized bodies plotted in identical fashion on two ΔT curves repeated on a specific route. It is obvious that if the solution is to coincide with an accuracy corresponding to the accuracy of the graphic and mathematical operations required to compute the depth and other components of occurrence, the accuracy of measurement of the field must be taken as adequate for the methods of calculation of depth now available. However if the divergence is expressed in some tens of per cent the accuracy of measurement must be recognized to be unsatisfactory for solution of the geological problems in question. Only this provides a basis for understanding the requirements for accuracy in measurement. However, as no such research had been performed and as the accuracy of calculation of the components of occurrence reveal a direct connection with the accuracy of the starting data, one may fully understand the requirement that the maximum accuracy capable of being attained by today's techniques be attained. It is necessary to strive for accuracy of measurement along short sections of route equivalent to the test-stand accuracy of the instruments. This comes to about $\pm(5\gamma + 1\%)$ for the T-aeromagnetometers now in use.

The effect of errors in orientation in the horizontal plane requires no extensive explanation. Points for which depths have been calculated and contours of bodies arrived at by calculation will be displaced to a magnitude equal to the error in orientation. The error in determination of altitude will enter in its entirety into the error in calculation of depth.

After all the ΔT curves have been examined in the working plane to determine the credibility of changes in field observed by the survey, curve segments are selected for use in calculating depth and other components of occurrence and also the intensity of magnetization of the rocks. When methods of calculation are used which have been developed for bodies of limitless extent, the appropriateness of these segments has to be determined. The choice of method for solving the problem of depth of occurrence depends upon the type of ΔT curve. Where isolated simple anomalies are concerned relatively simple methods of calculation may be used, but for all others the methods have to be those suited to analysis of complex curves and, in particular, the higher derivatives.

22. Elaboration of Magnetograms for Compilation of Magnetic Field Maps

Maps of magnetic fields, shown as isolines in 2-dimensional depiction, cannot be used to calculate the components of occurrence of magnetized bodies with the accuracy with which this may be done when the magnetograms themselves are used subsequent to the elementary processing set forth in the preceding section. The reasons are in the first place the fact that the map of a magnetic field is the product of complex elaboration of the raw data, the result being that additional errors are unavoidable. In the second place the map presents a levelled-out field in which many details needed to calculate the components of occurrence have either completely disappeared or are reflected improperly.

Maps of ΔT isolines generally contain errors which represent the results of inaccurate allowance for zero creep and some degree of error related thereto in determination of the normal field. These errors may attain large dimensions in T aeromagnetometer survey as is indicated by experimental determinations of zero creep, which is sometimes not only not linear but even reveals change in sign in the course of a flight. Due to these errors the level of the field taken as normal may along certain segments of adjacent routes differ by some tens or even by hundreds of gammas.

In drawing the isolines this divergence is expressed in smooth inflexion of the line and, if it goes into the geological interpretation, it may result in an erroneous impression of the geological structure at the given point. The ΔT curves based thereon and used to calculate depth and other components of occurrence will differ significantly from the initial curves due to an unavoidable levelling-out.

These large errors, which are of no significance when the original curves are used to calculate depths and other components of occurrence, render it impossible for the isolines on the maps to be of high accuracy in terms of changes in the field over a comparatively brief interval, equal to the width of the anomaly. As a matter of necessity the intervals between isolines are chosen in such fashion that many important details of the fields disappear therein.

The errors under consideration may be reduced considerably by checking the zero line at brief time intervals in the course of the survey. But in this case too it is not possible to use equal, small intervals between the isolines, as the presence of intensive anomalies with large gradients would demand impractically close spacing of the isolines at many points.

Under these conditions gradually increased intervals are the normal solution. When this procedure is followed virtually all the slight variations in field in the region of strong anomalies

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disappear, a phenomenon that seriously affects the differentiation of the rocks.

This unavoidable smoothing over of the field as it is depicted in isolines leads to a situation in which aerial magnetic maps compiled on the scale of the survey are incapable of reflecting the details of geological structure in accordance with the given scale. They are capable of being used only to reveal significant peculiarities in the geological structure of the given territory and consequently they are compiled so as to serve the purposes of small scale mapping.

The importance of this procedure is not subject to question, as determination of the special features of the magnetic field over large areas by a general examination of an isoline map (or of a small scale Z graph, in surveys with the Z aeromagnetometer) provides very valuable data for clarification of the general geological structure and in some cases for the selection of areas offering good prospects for seeking useful resources. Let us cite the well known examples from the West Siberia survey, in which the regular arrangement of the anomalies testifies to the existence of folded strata under thick sedimentaries, or the East Siberia survey, where unique changes in field have permitted the mapping of effusives, or the survey of the European north, where overall maps revealed the existence of large structures, important in determining the directions in which prospecting should be conducted, etc.

For the purpose of compiling maps of the magnetic field, the measured values of Z or ΔT must be freed of components introduced by daily variations in field, normal gradient of the field, uncompensated residue of the mean value of the normal field, and those variations in the readings of the measuring instruments which are not related to the measured magnetic field.

Special allowance for variations is not nearly always necessary, even in work with the T aeromagnetometer.

If the control instruments recording the variations show them to follow a smooth course in one direction during the period that the instrument is operating in the air, changes in the instrument readings go into the total magnitude of the "zero creep" and are eliminated on correction for zero creep.

However, if the control instruments recording the variations show them to follow a nonlinear course, with considerable amplitude, special correction for variation is necessary, as in this case changes in field cannot be regarded as proportional to the time factor.

An exception is to be noted if intermediate control measurements are run in the process of the work at intervals in which the variations occur in approximately linear fashion.

In the northern latitudes, correction for variation is essential.

Measurements during powerful magnetic storms are hardly subject to correction. The question as to the possible introduction of corrections is resolved in each separate case in accordance with the amplitude and frequency of the fluctuations in the intensity of the field. If it is impossible to make these corrections the measurements must be repeated.

Corrections for change in temperature are made independent of other corrections if the fluctuations in temperature were considerable and the sign of the temperature changed. In practice the question is resolved in terms of the relationship between the maximum correction for temperature and the correction for zero creep. If the former correction constitutes a small fraction of the latter (let us say, less than 10%), then one may dispense with correction for temperature as it becomes part of the general correction for zero creep. If the effect of temperature is small the correction must be made separately and the zero creep is corrected in accordance with the control measurements after correction of the measurements on the check route for temperature.

Correction for zero creep is performed by measurement of the field on a check route before and after completion of the work on the working routes. Should the magnetometer be housed within the aircraft and the instrument readings show change in course to have a marked effect, the check route measurements are run on the outgoing and incoming trips parallel to the working course. If the sensitive element is carried overboard, measurements on the check course are run in one direction at uniform intervals and at an identical altitude.

Let us consider the magnetic field on the check course to be the normal and the instrument readings on the course to be the mean ordinate of a curve relative to the zero line on the tape. Let us designate the mean ordinates before the start of work on the outgoing flight as A_1, and on the incoming as A_2, with B_1 and B_2 having the same meanings after the completion of the work.

When the instrument functions normally the divergence of the zero values on the outgoing courses prior to and after completion of the work, constituting A_1-B_1, and that on the incoming courses, constituting A_2-B_2, must be identical and determine the change in

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the zero point during the time interval between check measurements. The difference A-B is determined for the T-aeromagnetometer in relation to the measurements made in one direction only.

Taking the changes in the zero value to be proportional to the time factor, let us calculate the ordinates of the arbitrary "normal" field at the beginning and end of each working trip, relative to the zero line of the tape, on the formula

$$y_t = A + \frac{A-B}{t_1-t_2}(t-t_1),$$

in which t_1 and t_2 represent the time periods to which the check measurements A and B pertain; t is any given moment in time in the interval between t_1 and t_2. The values A_1 and B_1 or A_2 and B_2 are substituted in the formula, depending upon the direction of the routes.

Determining y_t for the beginning and end of each working route, let us connect the ordinates found by direct lines, in relation to which the ordinates of the continuous curve recorded on the working route are determined. The lines for the base value will slope if the measurements on the check course before and after the work diverge. However, if the instrument readings on the check route are identical, the base lines will be horizontal.

In cases where repeated measurements are taken along a number of segments of working courses during a single flight the zero line creep is determined by the measurements on the check course and repetitions on the working courses. In order to provide for the latter the mean ordinates ΔT or ΔZ are calculated on each segment of repeated measurement (as for the check route) and this value is applied to the midpoint in time of the work conducted along the given sector. In accordance with this data the zero-point creep curve is drawn to correspond with the graph shown in Figure 51, where time is plotted on a definite scale on the x axis and the average field values in gammas are plotted on the y axis.

Let the average time reading for the measurements on the check course be t_1 at the beginning of the work and t_6 at the end. The corresponding values of the mean ordinates on the check course will be $\triangle T_1$ and T_1'. If no intermediate control measurements have been made, the straight line connecting points the values of which are $\triangle T_1$ and T_1' will determine the drop in the zero point at any given moment in the interval t_1-t_6. In the given case repeat measurements were made on 2 segments during the intermediate moments t_2 and t for one segment, and t_4 and t_5 for the other. Let us write the corresponding mean values of $\triangle T$ and connect them with straight lines which govern the change in the zero point during shorter periods of time. These 2 straight lines show that the creep was faster at the outset and slower at the end of the work. Employing these supplementary measurements let us trace a curve between points $\triangle T_1$ and $\triangle T_1'$, the segments of which in the corresponding intervals will approximately parallel segments $\triangle T_2$ -$\triangle T_2'$ and $\triangle T_3$ -$\triangle T_3'$. The curve thus drawn is used to correct for zero creep as a more accurate approximation of reality than the straight line segment $\triangle T_1$-$\triangle T_1'$.

After correction for variations, temperature and zero creep (each separately, in accordance with the causes of each, and either in the stated order or as a gross correction for all if the variations in temperature constitute only a small fraction of the total zero creep) the values observed are subjected to further processing.

If the check course has been laid in the normal field the $\triangle Z$ (or $\triangle T$) curves drawn on this basic value will represent the sum of the anomalous values and of the increase determined by the normal gradient of the field, depending upon the geographical coordinates of each point. However, if the check course is run in an anomalous field, all the ordinates of the curves along the various courses will contain an additional constant, equal to the difference between the normal field and the field on the check course. Before the curves on the check course can be applied to the normal field, they must be freed of the normal gradient. This factor may be determined by the maps for the normal magnetic field of the territory of the USSR compiled by the Institute of Terrestrial Magnetism. The gradient is determined in 2 direction, parallel and perpendicular to the working courses, in gammas per kilometer. However it should be borne in mind that the maps of isodynes and other components for the weakly populated portions of the territory of the USSR have been compiled on the bases of a very widely spaced net of absolute magnetic measurements, so that these maps represent approximations to a very considerable degree. Therefore when aerial magnetic work is done in poorly inhabited or uninhabited areas, where the absolute measurements have been made on widely spaced courses (along large rivers, caravan routes, etc), the data of aerial magnetic survey is needed to determine the normal gradient.

Let us first examine the question as to the constancy of the normal gradient on the large territories covered by aerial survey.

Assuming that the normal field is that of a uniformly magnetized sphere along its axis of rotation, we find from equation (4.1) that

$$\frac{dZ}{dx} = -Z_{max}\frac{\sin\theta}{r},$$

$$\frac{dH}{dx} = Z_{max}\frac{\cos\theta}{r},$$

in which $dx = rd\theta, \theta$ — is the supplement to the latitude of the given locality and r is the radius of the earth.

Assuming that Z_{max} is 60,000γ, we find that for 60° N lat $\frac{dZ}{dx} = -4{,}5\gamma$, while for 50° it is $50° \frac{dZ}{dx} = -6\gamma$ per km, indicating that the theoretical gradient varies by 1.5γ over a distance of 1,100 km along the meridian. Under the same conditions the $\frac{dH}{dx}$ gradient will be 5.9γ and 3.4γ per km respectively.

The gradient of the total vector in the meridional direction will be

$$\frac{dT}{dx} = \frac{dZ}{dx}\sin I + \frac{dH}{dx}\cos I;$$

under the same given conditions, while when I is 65° it is -2.5 γ and -4.0γ per km. With the given specific values for latitude, the T gradient declines in absolute value relative to the Z gradient, but the relative change in the gradient increases over the distance of 1,100 km. In reality it is necessary to examine the gradient of the total field of uniform magnetization of the sphere and the continental anomaly. The latter is known only by occasional observation points and is incapable of determination with the required accuracy. Its influence may either increase or decrease the calculated particular values of the gradient along the meridian and create a considerable gradient by latitude.

In any case it must be borne in mind that over distances exceeding approximately 500 km the normal gradient cannot be regarded as a linear function of the distance.

In order to determine the normal gradient let us employ the method used by magnetologists to find the normal field of large territories on world maps, employing absolute measurements.

In accordance with measurements corrected for variation, temperature, and zero creep let us set up a map of the magnetic field in the form of $\triangle Z$ or $\triangle T$ curves along the flight courses or else let us enter only the numerical values at specific intervals in accordance with the scale of the survey. Let us find the average value of the intensities in squares 10 cm on a side and let us compile a map of $\triangle Z$ or $\triangle T$ isodynes in accordance with the values thus determined. Now let us investigate the possibility of drawing smoothed isolines, approximately parallel to each other, without paying attention to the closed coutours of the true isolines, which represent local anomalies, although they may be large. If this effort is not successful the sides of the squares used to find the mean values may be further increased. This is entirely within the realm of possibility when the scale of the map is large enough to provide the needed number of points with mean values for plotting approximately parallel isolines. The difference in the values of the parallel isolines, divided by the distance S, between them expressed in km will be the gradient of the field in the S direction.

A similar method of finding the gradient of the normal field has been used by several field workers in accordance with the results of preliminary survey along widely spaced courses. There is no need to run preliminary surveys along widely spaced routes when it is possible to utilize the data of the total survey for the same purpose, with better results.

Thus the field gradient may be determined either by maps for the normal magnetic field of the territory of the USSR or by the data of aerial magnetic survey. Let us say that it will be "a" gammas in the direction of the course, and "b" gammas per kilometer in the direction perpendicular therto. Taking the midpoint on the check course as the origin of rectangular coordinates, the direction of the flights is taken as the ϵ axis and the direction perpendicular thereto as the η. We now determine the correction for normal gradient at any point on the working routes. If the gradient has proved to be a linear function of the coordinates, which would be the case where relatively small areas are concerned, it is adequate in practice to determine the corrections for the start and finish of each route and to connect the corrected coordinates of the ends by a straight line, which will be the corrected base line. The equation for introduction the correction will have the simple form

$$\gamma_g = a\xi + b\eta,$$

where ϵ and η are given in kilometers as the distances from the mid-point on the check course to the given point on the route. The sign for the correction depends upon the signs of a and b in the directions of the coordinate axes selected. The calculated correction must be subtracted from the values of the ordinates of the given points.

For example let us assume that the survey is made along meridional routes 120 km in length, that there be 80 flights in all, at 2-km intervals, and that the landing strip and check route be in the center of the area covered. Let us assume the normal gradient determined by one of the methods cited above to be 3.5γ in the direction of the flights (the field increasing to the north) and $2.2\,\gamma$ in the direction normal thereto (the field increasing to the east). Then we reduce the southern end of the zero line on the middle flight course by $210\,\gamma$ (increasing the ordinate accordingly) and raise the northern end by 210γ. We follow the same procedure with the zero lines of all other courses, leaving them parallel to the corrected zero line of the middle course, but gradually shifting them by a magnitude corresponding to the normal gradient in the east-west direction. For example, on the twentieth flight east of the middle, and thus 40 km from the check route all the ordinates in the curve are reduced by 88γ or in round figures by 90γ. Therefore the extreme northern ordinate is reduced by 300γ, taking all factors into consideration, and the extreme southern is increased by 120γ. On the thirtieth route to the west of the check course all the ordinates are increased by approximately 130γ or in other words the ordinates of the extreme northern point are reduced by 80γ and those of the extreme southern are increased by 340, all factors taken into consideration. If the gradient is not linear, which will be the case almost always in surveying very large areas, the entire area may be divided into smaller segments, within the limits of which the gradient may be regarded as a linear function of the coordinates, and in which the corrections are made separately for each.

The ΔZ or ΔT curves, corrected for normal gradient, differ from the curves of an anomalous field, if the check routes has been plotted in this field.

In order to find the constant by which all the ordinates have to be corrected or in other words in order to reduce all the measurements to a normal field, we make use of the conclusion, derived from the theory of the magnetic field of magnetized bodies, to the effect that the magnetic flow over a magnetized object of large extent, along a line transecting the entire anomaly normal to its axis, must equal zero. This conclusion follows from the general physical concept of the lines of force in a magnetic field and may be proved mathematically.

Let us limit ourselves to an examination of the field of a horizontally elongated body of any constant cross-section, for which the equation of the Z curve transverse to the trend is expressed by the formula:

$$Z = 2I \iint_{s} \frac{(x-a)^2 - c^2}{[(x-a)^2 + c^2]^2}\, ds,$$

in which I is magnetic intensity, s is the cross-sectional area, a and c are the coordinates of a component of the area of cross-section ds, and x is the running coordinate.

Let us demonstrate that

$$\int_{-\infty}^{\infty} Z dx = 2I \iint_{s} \left[\int_{-\infty}^{\infty} \frac{(x-a)^2 - c^2}{[(x-a)^2 + c^2]^2} dx \right] ds = 0.$$

Let us write $x-a = ct,\ dx = cdt$

$$\int_{-\infty}^{\infty} \frac{(x-a)^2 - c^2}{[(x-a)^2 + c^2]^2} dx = \frac{1}{c} \int_{-\infty}^{\infty} \frac{t^2-1}{(t^2+1)^2} dt = \frac{1}{c} \int_{-\infty}^{\infty} \frac{dt}{t^2+1} - \frac{2}{c} \int_{-\infty}^{\infty} \frac{dt}{(t^2+1)^2} =$$
$$= \frac{1}{c} \left[\int_{-\infty}^{\infty} \frac{dt}{t^2+1} - \frac{t}{t^2+1} \Big|_{-\infty}^{\infty} - \int_{-\infty}^{\infty} \frac{dt}{t^2+1} \right] = 0,$$

which is what it was required to prove.

The consideration thus demonstrated will be valid relative to 3-dimensional objects when the integral is based on the area.

From this it follows that if the average value of $\Delta Z_{cp} = \frac{1}{n} \sum_{i=1}^{n} \Delta Z_i$, calculated on a series of successive flight course, is zero the normal field has been chosen correctly. However if the average value is positive the normal field is too low and the zero line must be raised by that average value. On the other hand the zero line must be reduced if the average value is below zero. In the formula ΔZ_1 represents the ordinate of the ΔZ curve at points determined at equal intervals, that is, 0.5 or one km, and n represents the number of points employed.

Analogously it may be proved that $\int_{-\infty}^{\infty} H dx = 0$, in view of which the adduced rule may also be applied to measurement of ΔT, to the same degree of approximation for which equation (2.2) is valid.

After the residual normal field has been subtracted, there remain the changes in the field produced only by the change in geological structure plus errors of measurement and calculation.

In actual practice aeromagnetic parties taking surveys with the Z aeromagnetometer most frequently employ a simplified method of determining the normal field. This method consists of the fact that the zero line is drawn on the original magnetogram in the form of a straight zero line is drawn on the original magnetogram in the form of a straight line most nearly approximating the $\triangle Z$ curve on the tape, that is, in accordance with the requirement that the positive and negative areas bounded by the given zero line and the $\triangle Z$ curve be equal. This eliminates at one stroke the effect of smooth change in the zero value and the normal gradient of the field. Under favorable conditions this method of selecting the normal field may lead to the same results as curves oriented on the check route after the successive operations have been performed. Favorable conditions consist primarily of the absence of large anomalies, the choice of course normal to the trend of the anomalies, and stable operation of the instrument. In the absence of these conditions there are inevitable serious complications in the elaboration of the field data and a map of the magnetic field made in this manner does not guarantee proper depiction thereof on the regional scale.

The accuracy of the choice of zero lines along the routes in this simplified fashion is checked by plotting secant courses perpendicular or almost perpendicular to the main course. The zero lines on the main routes are equalized in accordance with the values of the field on the secant routes.

This method of correcting the zero lines is permissible only when there is a field so quiet as to be almost homogeneous. Where clearly defined anomalies exist, crude errors may occur as a result of the lack of precision in determination of points of intersection with the routes and as a result of divergences in the field due to variations in flight altitude.

23. Presentation of the Results of Aerial Magnetic Studies

The results of aerial magnetic researches performed to solve geological problems are organized into final form by the presentation of a report and graphic adjuncts, the content and list of which are specified in the instructions.

There is no need for a fundamental reexamination of the data specified for inclusion in the reports of Z aeromagnetometer surveys, as the basic geological conclusions are developed on the basis of a general examination of maps of the magnetic field compiled in the form of Z_a maps, without calculations of depth and other components of the occurrence of magnetized bodies. Geological conclusions would be illustrated more satisfactorily if maps of the magnetic field Z_a were accompanied by depictions of the contours of rocks having various magnetic properties or by adduction of lines showing major tectonic disturbances and other major structural elements. In certain cases this is possible. It must be striven for where attainable, as the graphic presentation of geological conclusions described in the text always demands more profound elaboration of the data and raises the standards which must be met.

The standards to be met by graphic appendices compiled on completion of elaboration of T aeromagnetometer survey are in need of reexamination, the major problem being the reflection of the geological results in graphic form.

The T aeromagnetometer is used primarily in platform regions, where magnetic data of high accuracy may be successfully used to calculate the depths of magnetized bodies and the subsequent development of the relief of the platform basement, as anomalies are primarily due to basement rocks. Calculation of depths and other components of occurrence also provide very valuable data for the solution of many other important questions in the study of geology. Determination of the intensity of magnetization of the rocks giving rise to anomalies provides data on which one may follow rocks of homogeneous composition and differentiate and distinguish rocks of various magnetic intensities and thus different in composition or origin.

These briefly formulated possibilities in the magnetic method are presently used to only a negligible degree. Final reports generally are accompanied only by maps of the magnetic field in one form or another, textual descriptions of anomalies, and general geological conclusions. These conclusions, converted into the language of graphs, utterly fail to correspond in accuracy and detail of graphic representation to the scale of the survey performed. Thus the chart of the folded formations of Western Siberia, based on the general distribution of the magnetic field determined by surveys varying from 1:1,000,000 to 1:200,000 in scale, actually represents no more than an outline. There is no doubt as to the great value of this sketch map but neither can there be any as to the fact that it is entirely out of correspondence with even the finest scale of the aeromagnetic survey.

In an effort to draw general conclusions from aerial magnetic surveys that have been run over large territories, including that of Western Siberia, many organizations are attempting to employ the magnetic field maps accompanying the final reports here under discussion in order to offer a more profound geological interpretation.

That is to say they are trying very late in the day to perform the chief function which in the essence of things should have been done by the aeromagnetic expedition that had run the survey. There may be efforts to prove that the survey work and that of maximum geological utilization of the data ought properly to be separated. Such efforts are inherently unconvincing. In the first place the instructions now in force envisage that the report include geological conclusions. In the second place transfer of aeromagnetic survey data from the expedition that has gathered it to some other organization for geological interpretation is not provided for by any regulations whatever.

The organizations occupied with elaboration of the material accumulated usually have ready maps of the magnetic field available. The reports usually have appended many sheets of computations of mean square errors in order to facilitate critical evaluation of the accuracy of the measurements. The error calculated by measurements at points where flight course intersect is in no way related to quantitative analysis of the reliability of the field changes revealed within the framework of the particular anomalies used to calculate depths; their relationship to evaluation of the field values is quite remote. After all it is known that along particular course segments the errors exceed calculated levels several times over. This results chiefly from the nonlinearity of the zero creep and is readily discoverable on examination of the map, if it is presented in the form of ΔT curves along a pronounced high on some particular curve against a generally flat background that has been fixed beyond doubt by means of the curves on the adjacent courses. On isoline maps these errors are modified by the smoothed contours of the isolines and are therefore difficult to define.

The summary maps have been used to calculate depths by occasional scientists working with the data they contain. No doubt when isoline maps are used only on occasion the depths calculated will be more or less close to reality. However in the majority of instances depths are calculated on distorted curves differing from those originally derived. Therefore there is no basis for expectations of high accuracy in this situation.

The situation is somewhat better when the map employed is presented in the form of $\triangle T$ curves. However in this case virtually all regions with large anomalies and significant gradients are eliminated due to the intersection of the curves and the impossibility of deriving the needed curve with confidence. Areas with smaller anomalies are less reliable, as the numerous redraftings required in the course of the complex elaboration of the curves for purposes of map compilation, even small absolute errors in $\triangle T$ graphs are of relatively major significance.

Efforts to calculate depths and other components of occurrence on the basis of maps of magnetic field have created an inaccurate idea to the effect that depths cannot be calculated from magnetic data with satisfactory accuracy. This experience has had the objective effect of facilitating the dissemination of primitive methods of calculation which are incapable of providing good results even when measurements are of ideal accuracy. This deep-rooted practice must be completely uprooted. It cannot be shown that accurate magnetic measurements in geological conditions favorable to the magnetic method are incapable of yielding depths and other elements of occurrence as well as magnetic intensities by calculation with the same accuracy as the data of other geophysical methods including the seismic. On the contrary it may be stated that the possibilities offered by the 2 methods are identical as to principle but that the simplicity and ease with which magnetic fields are measureable are balanced off by the labor needed to elaborate this data.

The fact that large aeromagnetic expeditions do not include among their personnel specialists capable of doing geological elaboration of survey data in the process of field work is quite significant. On the other hand the time allocated for elaboration in the office is utterly inadequate for fulfillment of the required work.

It should be a universal rule that flight route ΔT curves should be used to find the depth of occurrence, dimensions and dip of magnetized bodies in vertical cross-section by geometrical plottings. Bodies described in cross-section must be divided into specific categories by magnetic intensity calculated on the absolute intensity of the anomalous field. Such calculations must be made for each flight course at all points where changes in the magnetic field permit employment of the methods of computation with which we are now familiar.

The accuracy of the findings for depth which may on rare occasion be verifiable by means of reliable independent, credible data (primarily by the evidence of bore holes) is generally checked by the degree to which the changes from one point to the next are logical in course and likewise by the logic of observed changes in other components of occurrence and by the degree to which the magnetic intensity for a given anomaly proves to be constant. Should points for which depths have been calculated be closely spaced (the data on Western Siberia is adequate to permit calculation of depths at 10-20 points per sq decim of map surface, given depiction of flight courses at one cm intervals), one is free to discard findings that are obviously unsatisfactory, while the remainder are used to depict the underground relief in the form of isohypses on the scale of the survey, either directly, or after averaging depths at points nearby.

Isohypse maps and series of typical cross-sections characterizing rocks by magnetic intensity should be the basic graphic appendices illustrating the geological results of the work of aeromagnetic expeditions on the given scale of survey.

Due to lack of experience in the compilation of such maps, it is thus far difficult to specify a desirable interval to be maintained between isohypses. In the general case this will depend upon the absolute depth of occurrence of magnetized bodies. Therefore in order to evaluate the accuracy with which subsurface relief has been depicted it is necessary to enter on the map all points with calculated depths used to compile the map and to indicate calculated values.

A map of the magnetic field in the form of isolines or ΔT graph should constitute the second graphic adjunct.

Depending upon the practical purposes to be served and the accuracy with which the field has been depicted, it is desirable to reduce the scale of the map by comparison to the scale of the survey. This map should serve as the basis and illustration for geological conclusions relative to the major structural shapes in the territory under study. It is clear that graphic appendices must under no conditions be in disagreement with each other and with established geological facts.

Supplementation of desk work on a scale such as to satisfy the requirements formulated above would bring about a marked improvement in the geological usefulness of high-accuracy aeromagnetics, which is now utterly unsatisfactory, and would substantially reduce costs in the general complex of geological research work in which the aeromagnetic method is employed.

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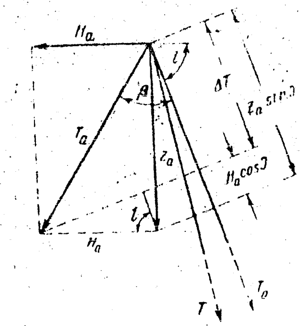

Figure 1. Geometric representation of the difference $\Delta T = T - T_o$.

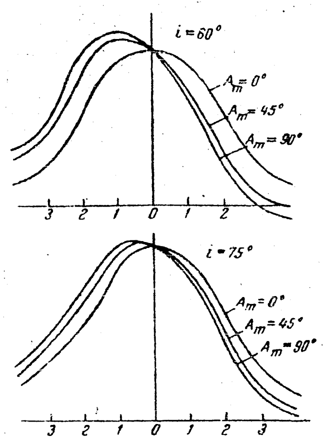

Figure 2. Variation in the theoretical ΔT curve over a vertical stratum of the thickness 2b = 2h at a depth of h = 1 relative to the azimuth of its strike A_m and angles of dip of 60° and 75°.

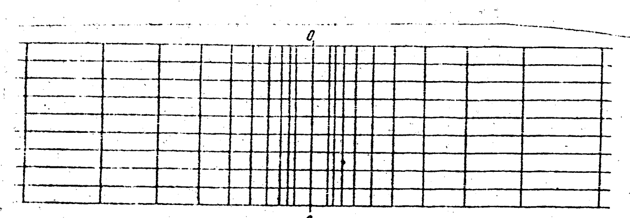

Figure 3. Graph layout for calculation of H_a for a given field Z_a, the problem being 2-dimensional.

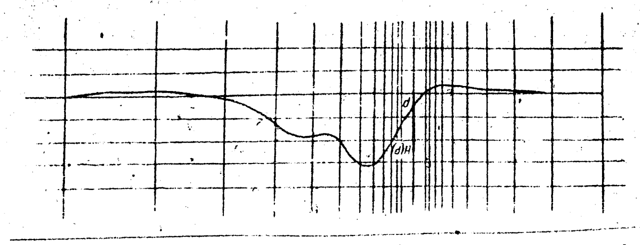

Figure 4. Specimen calculation of H on a given Z over a body of infinite course

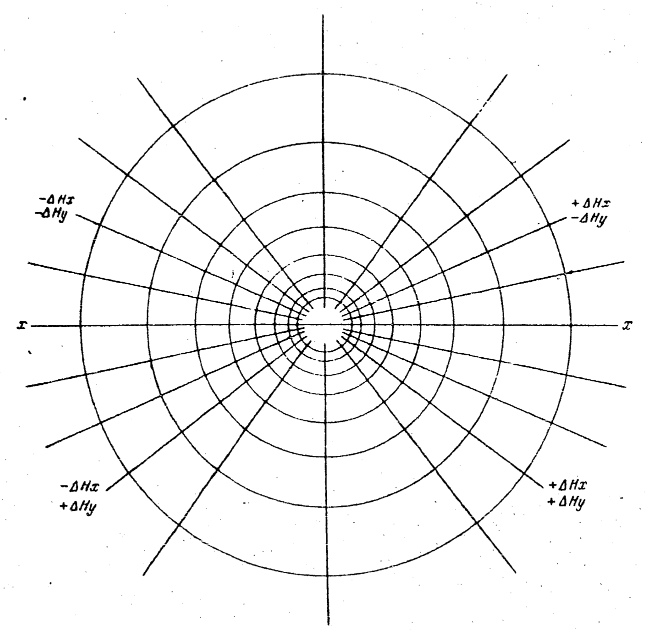

Figure 5. Graph arrangement for calculation of H_a on a given Z_a field, the problem being 3-dimensional.

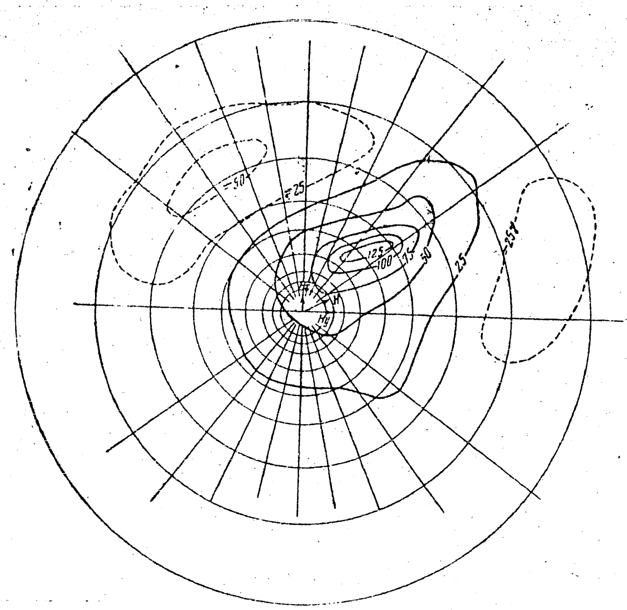

Figure 6. Specimen of calculation of H on a given Z over a body of indeterminate extent.

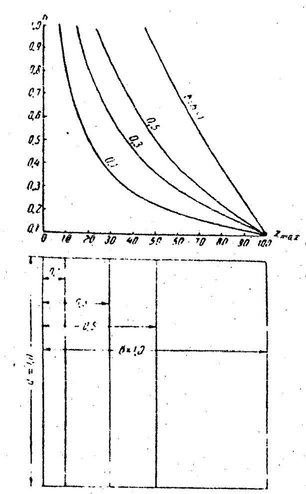

Figure 7. Curves showing change in Z_{max} with height above vertical strata of rectangular cross section and infinite course.

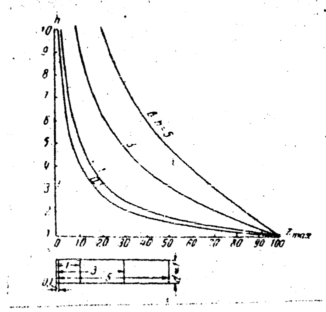

Figure 8. Curves showing change in Z_{max} with height, over strata of varying thickness.

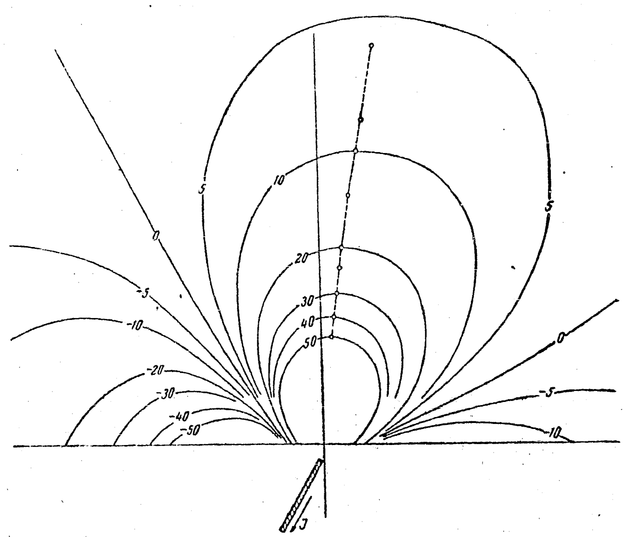

Figure 9. The magnetic field of an inclined stratum, vertical cross-section.

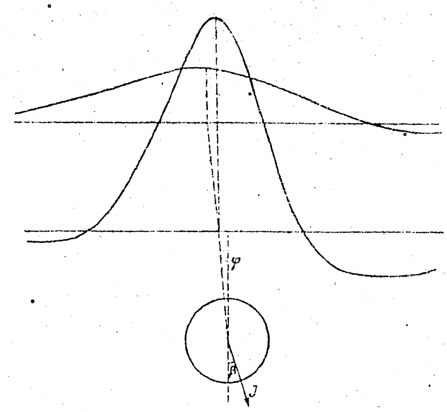

Figure 10. Displacement of Z_{max} along the [illegible] at varying levels above [illegible] cylinder.

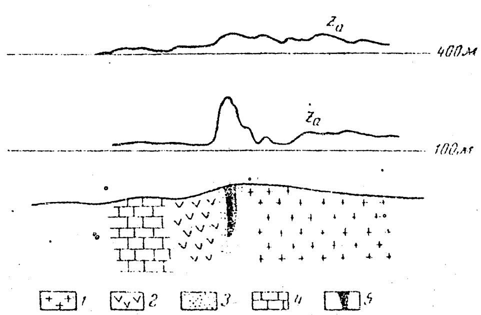

Figure 11. Variation in the [illegible] anomalies with fluctuations in the plane of observation over [illegible] contact origin. 1. [illegible] zone; 4. limestone; [illegible].

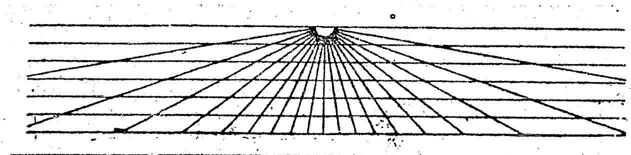

Figure 12. Graph layout for calculation of Z at a higher altitude, the problem being 2-dimensional.

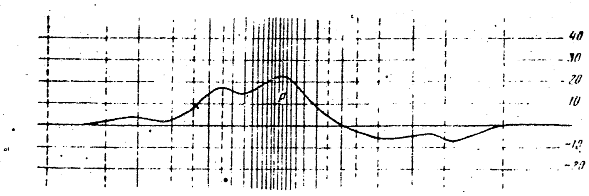

Figure 13. Specimen calculation of Z at a higher level in an instance of a highly elongated anomaly.

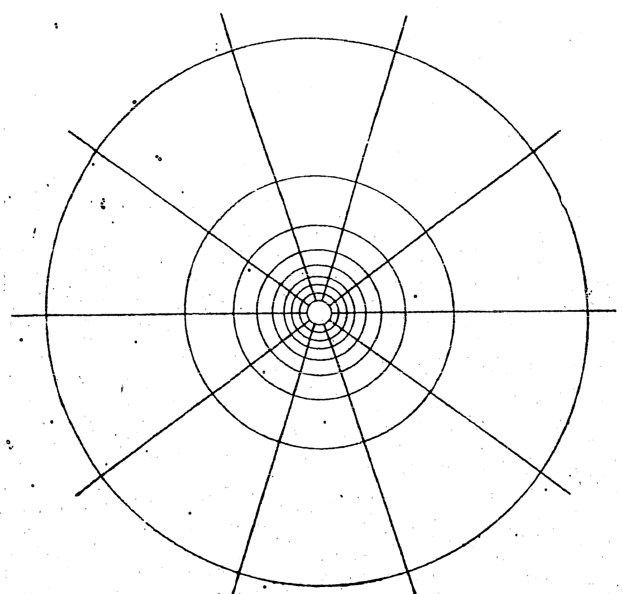

Figure 14. Graph layout for calculation of Z at a higher altitude, the problem being 3-dimensional.

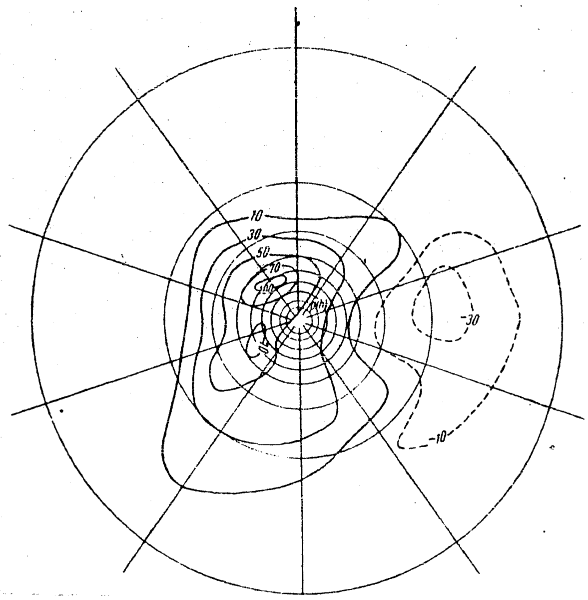

Figure 15. Specimen calculation of Z at a higher level, for an anomaly of indeterminate extent.

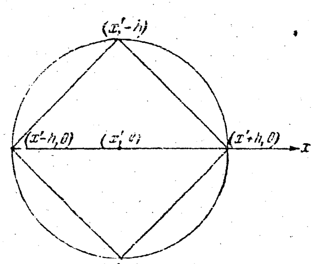

Figure 16. Point distribution pattern on calculation for level lower than the original.

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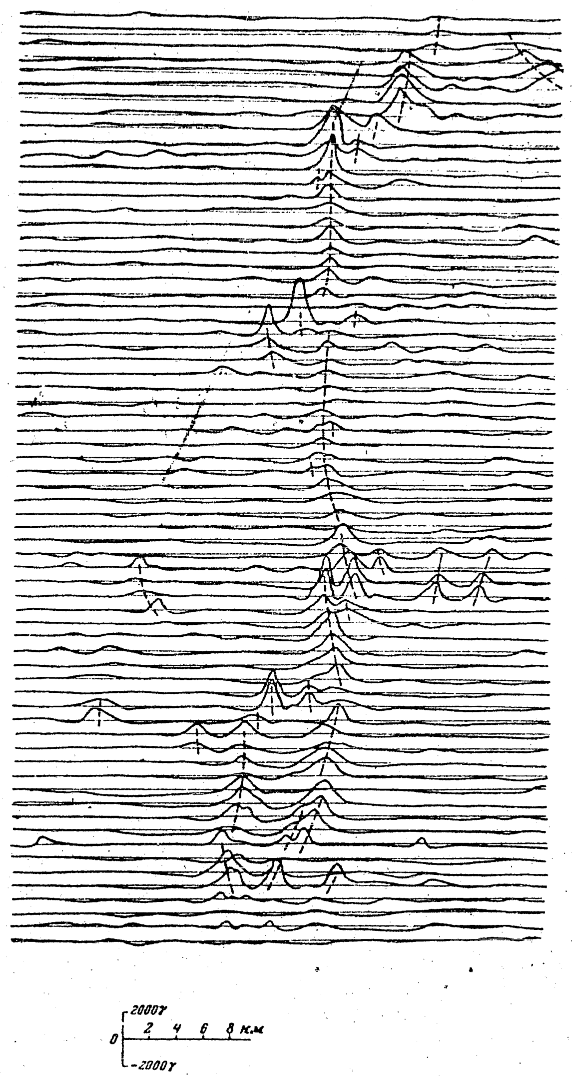

Figure 17. Z_a magnetic field of highly metamorphosed ancient rocks.

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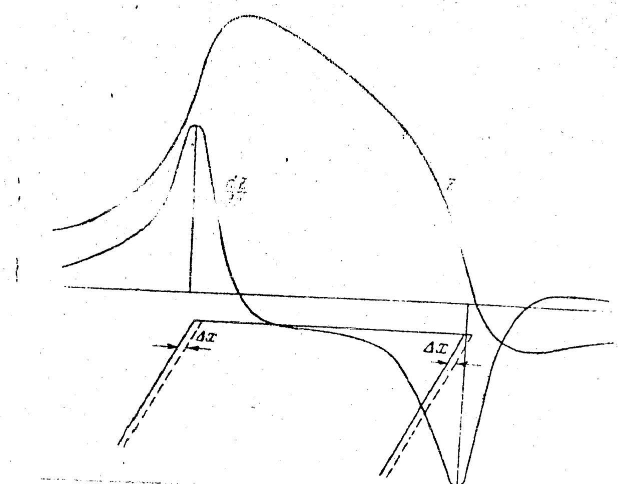


Figure 18. Z and $\frac{\delta Z}{\delta x}$ curves over an inclined stratum.

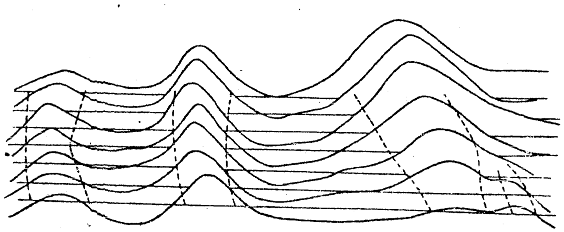


Figure 19. ΔT field over an area in Western Siberia.

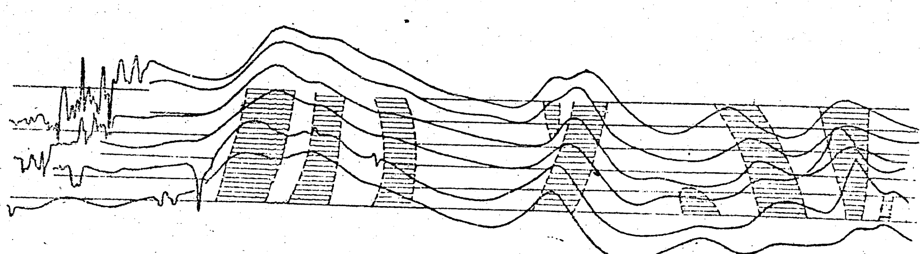


Figure 20. ΔT field over an area in Eastern Siberia.

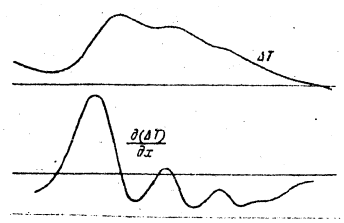


Figure 21. Complex ΔT anomaly and its differentiation along the $\frac{\partial(\Delta T)}{\partial x}$ curve.

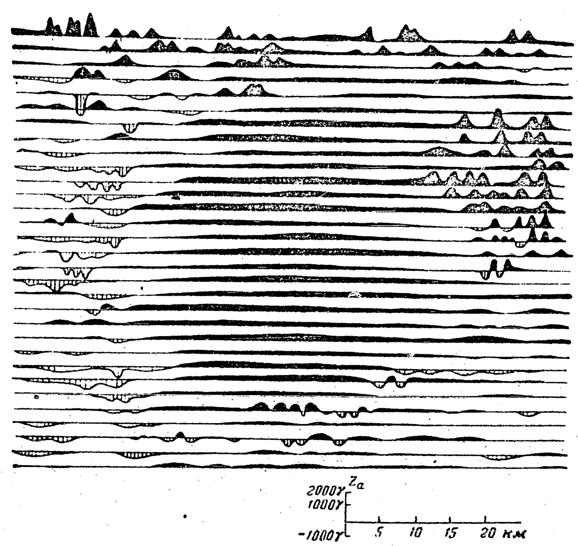


Figure 22. Identification of the contours of weakly magnetized rocks by means of very pronounced local changes in the Z field over the surrounding rocks.

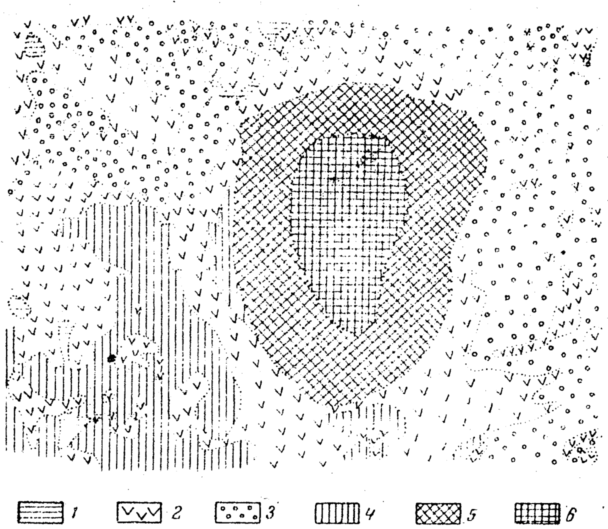


Figure 23. Schematic geological map of the area, the magnetic field of which is shown in Figure 22.

1. Quaternary deposits; 2. diabase traprock, gabbro diabase, etc; 3. tuffogenous stratum: diabase and prophyrite tuffs; 4. sandstones, shales, and clays; 5. Cambrian sandstones, limestones, and dolomites; 6. Pre-Cambrian strata.

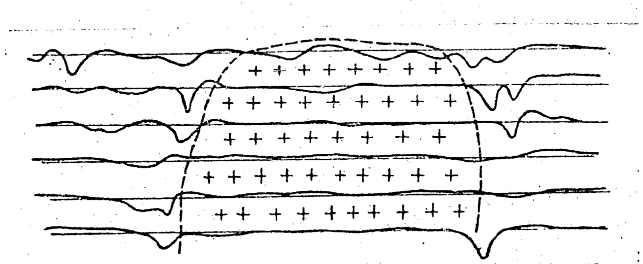


Figure 24. Differentiation of the contour of a granitic intrusion by changes in the magnetic field in the contact zone.

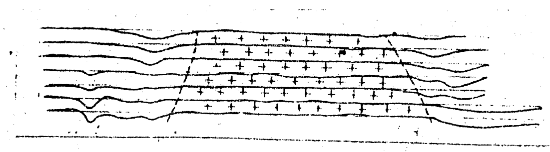


Figure 25. Differention of the contour of an intrusion by changes in the magnetic field over ore-bearing strata.

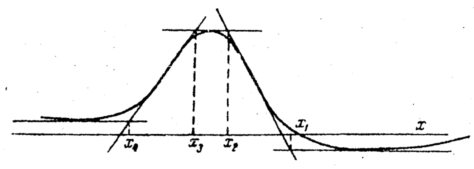


Figure 26. Determination of the depth of the top of a magnetized body by the points of intersection of tangents.

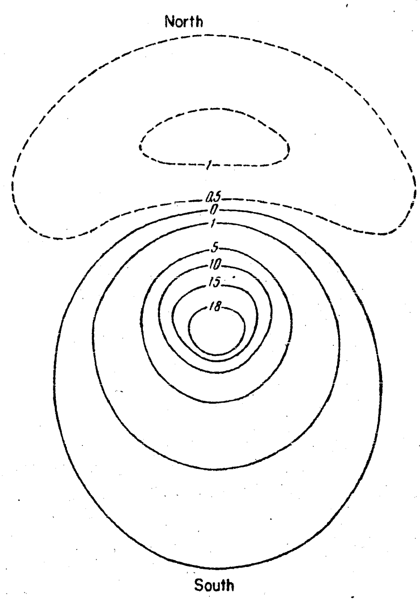


Figure 27. Z magnetic field in plan view over an obliquely magnetized sphere.

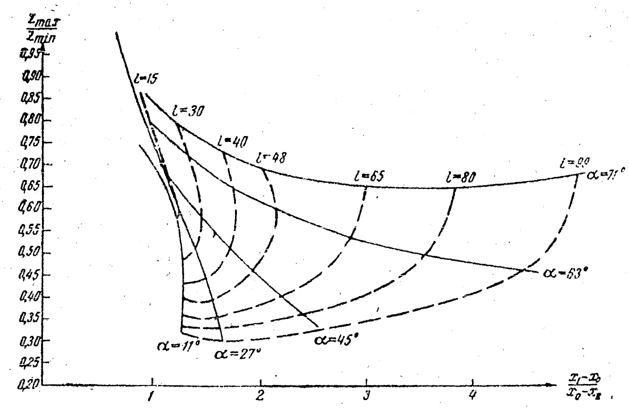


Figure 28. Nomogram for location of [illegible] of occurrence of a magnetized body on the basis of variations in the field over the [illegible].

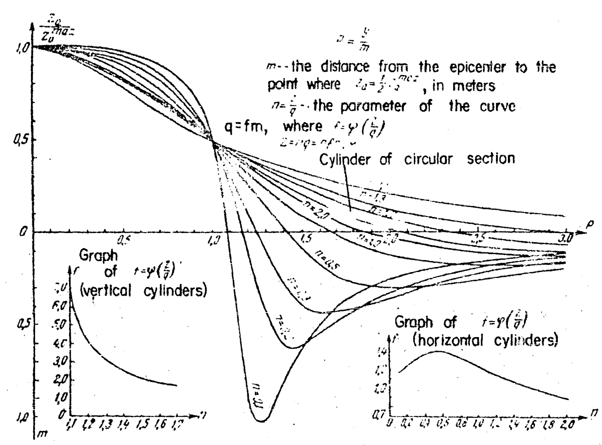


Figure 29. Nomogram for [illegible] of cylinders [illegible].

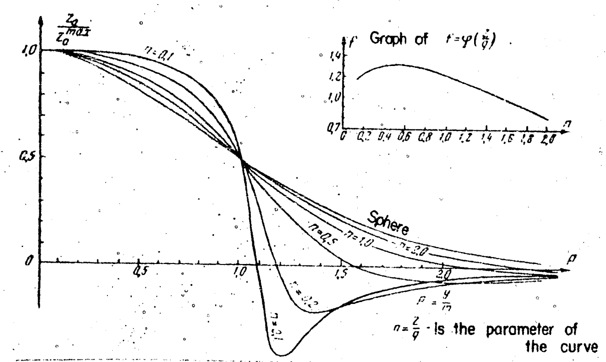


Figure 30. Nomogram for calculation of components of occurrence of ellipsoids of rotation.

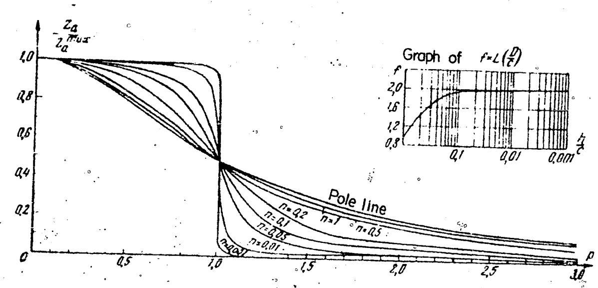


Figure 31. Nomogram for calculation of components of occurrence of vertical strata.

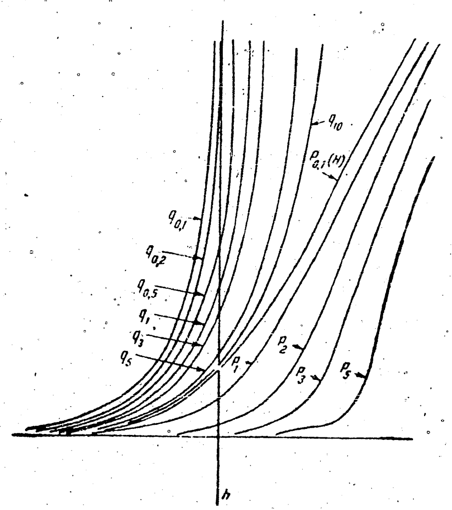


Figure 32. Nomogram in logarithmic scale for calculation of components of occurrence of vertical strata.

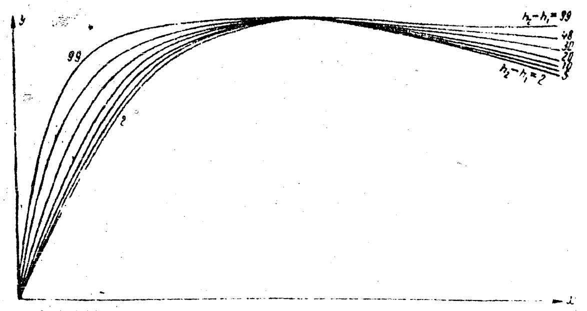


Figure 33. Nomogram for calculation of elements of occurrence of a body on the basis of changes in the field in the boundary area, with vertical dip.

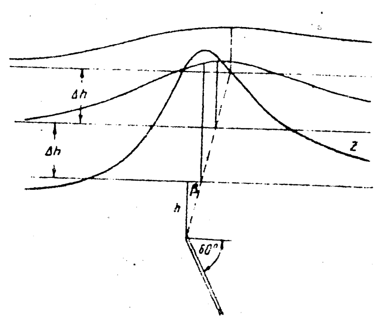


Figure 34. Calculation of the components of occurrence of a thin inclined stratum.

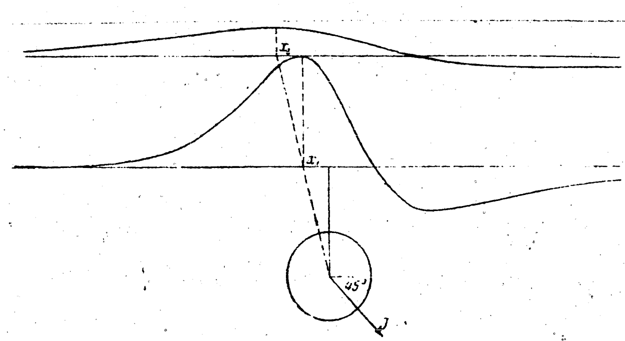


Figure 35. Calculation of the components of occurrence of a horizontal true cylinder, obliquely magnetized.

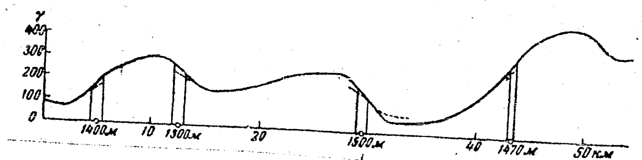


Figure 36. Specimen calculation of depth of occurrence of magnetized bodies by points of inflexion of ΔT curve.

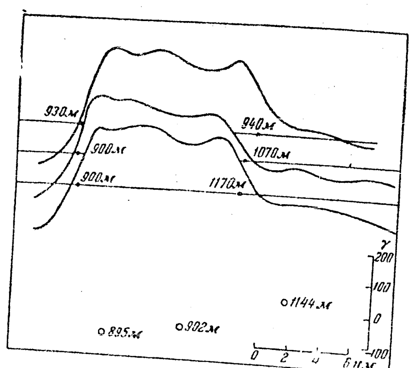


Figure 37. Specimen calculation of depth of occurrence of magnetized bodies by points of inflexion of ΔT curves.

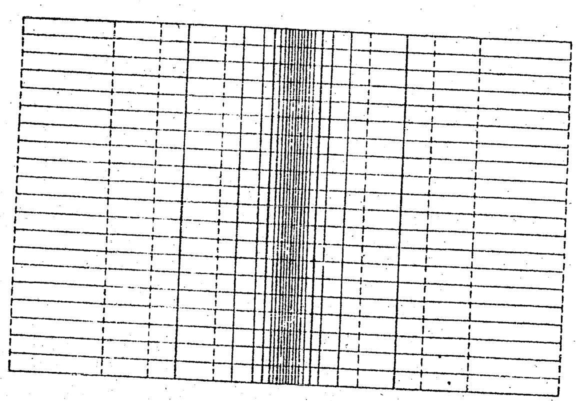


Figure 38. Graph for calculation of Z (or ΔT) field at a constant altitude equal to the intervals between the horizontal lines.

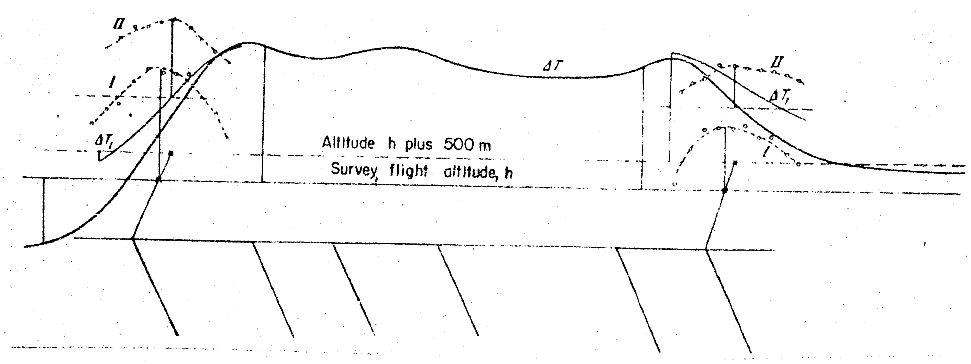


Figure 39. Specimen calculation of depth of occurrence and angle of dip in accordance with points of inflexion of ΔT curve.

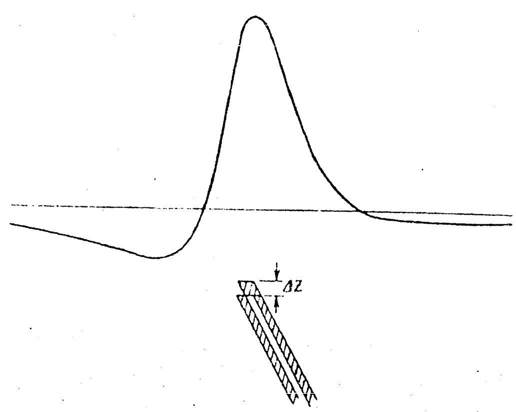


Figure 40. Geometrical interpretation of the second derivative $\frac{\partial^2(\Delta T)}{\partial x\,\partial z}$.

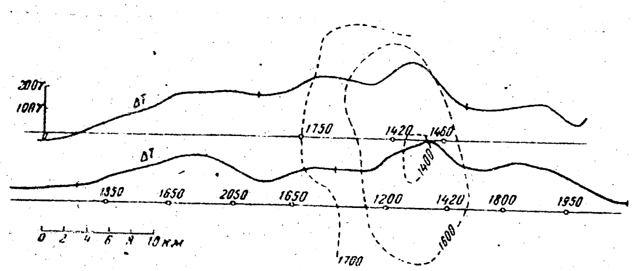


Figure 41. Specimen calculation of depths by second derivative $\frac{\partial^2(\Delta T)}{\partial x\,\partial z}$.

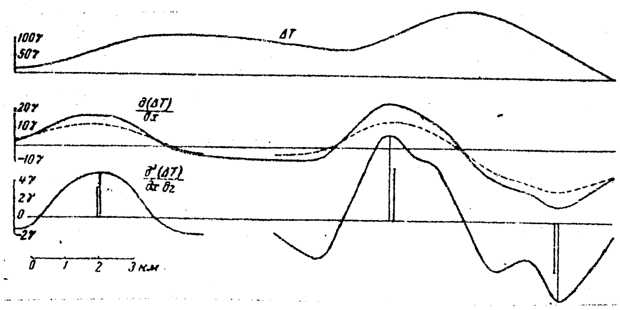


Figure 42. Calculation of depth by second derivative $\frac{\partial^2(\Delta T)}{\partial x\,\partial z}$.

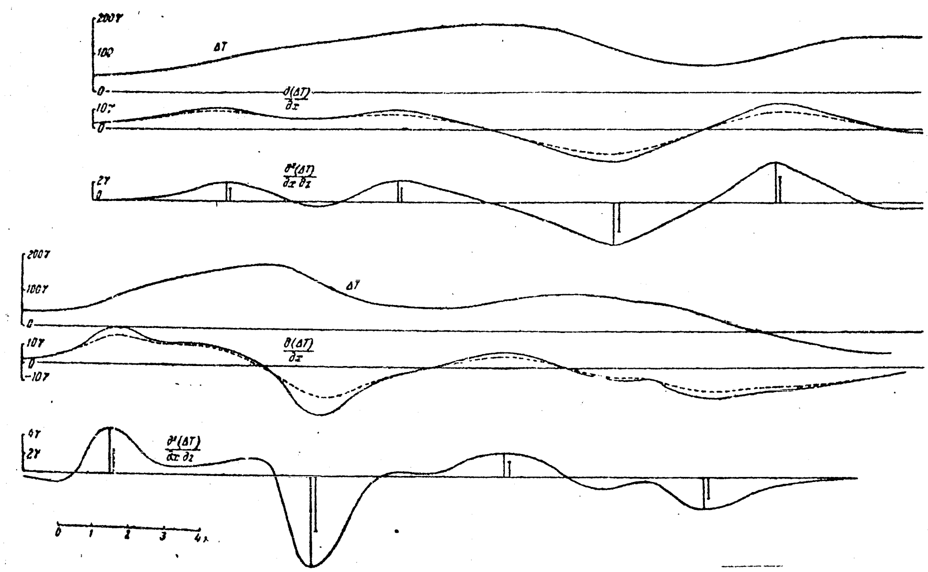


Figure 43. Calculation of depths by second derivative $\frac{\partial^2(\Delta T)}{\partial x\,\partial z}$.

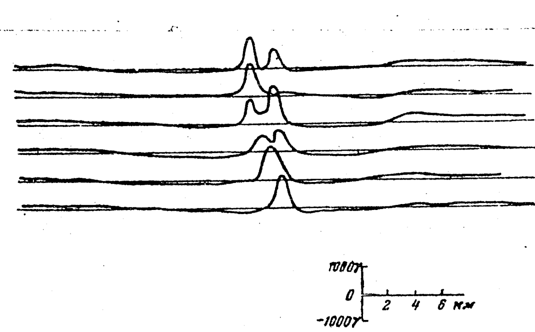
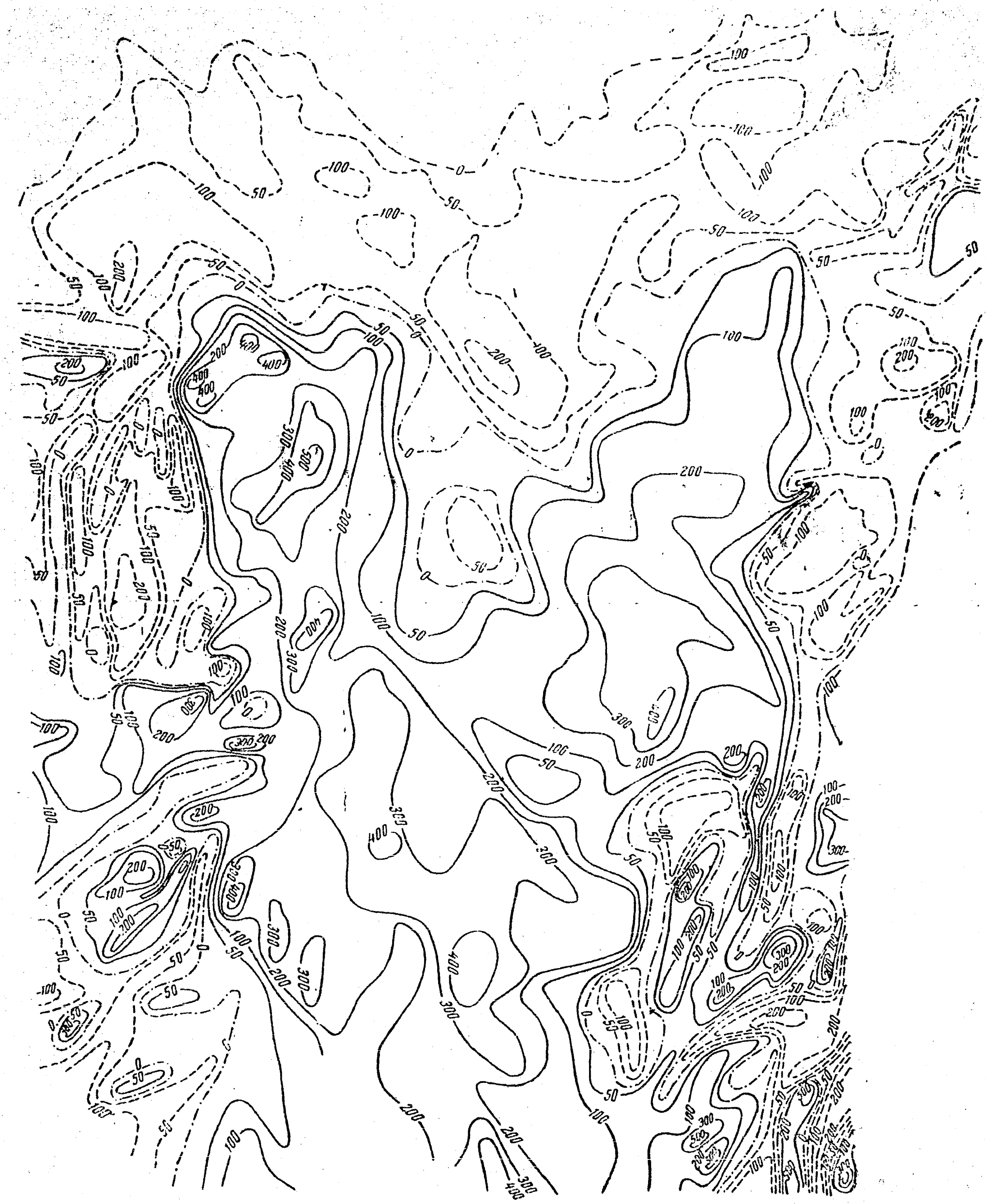


Figure 44. Typical Z_a anomaly over thin quartzites (about 10 m thick), from an altitude of about [illegible]00 m.



[illegible] 15. ΔT [illegible] over [illegible] depression [illegible] Siberia.

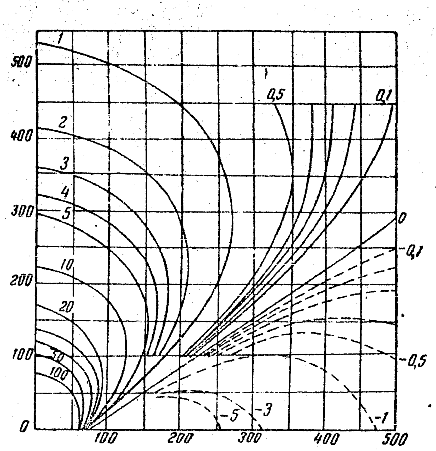


Figure 46. Change in Z field over a sphere, vertical cross-section.

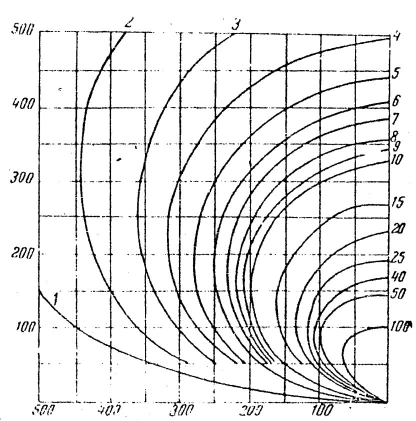


Figure 47. Change in Z field over a vertical rod, vertical cross-section.

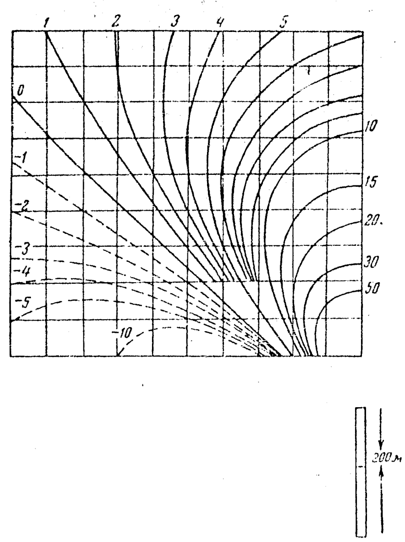


Figure 48. Change in Z field over vertical sheet, vertical cross-section.

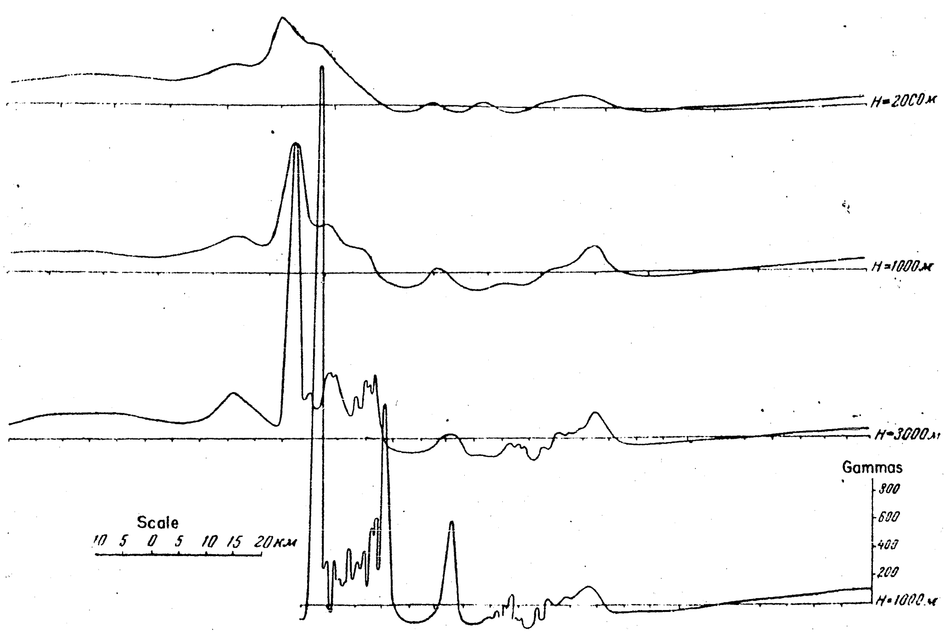


Figure 49. Results of measurement of ΔT field at various heights in a single vertical cross-section.

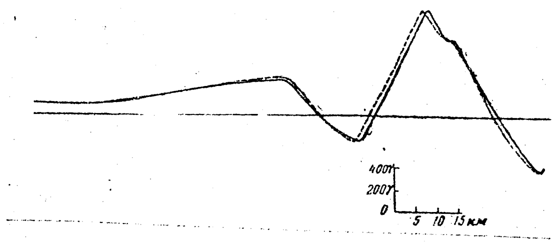


Figure 50. Repeated ΔT measurements on the same flight course.

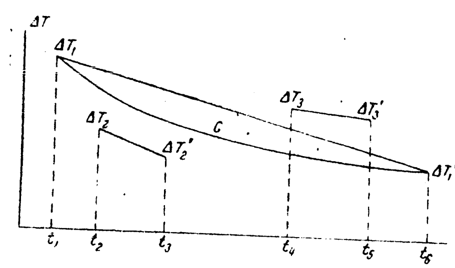


Figure 51. Curve of zero point creep, plotted on measurements over check route (ΔT_1) and repeated measurements on segments of working routes (ΔT_2 and ΔT_3).